

The Earth Observer. May - June 2018. Volume 30, Issue 3.

Editor's Corner

Steve Platnick

EOS Senior Project Scientist

On May 22, 2018 at 12:47 PM PDT (3:47 PM EDT), the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission launched from Vandenberg Air Force Base in California aboard a SpaceX Falcon 9 launch vehicle—see launch photo below—as a shared ride with five Iridium NEXT communications satellites. The twin GRACE-FO satellites successfully separated from the spacecraft over the Pacific Ocean and are now slowly drifting toward their operational positions.

Like its predecessor, GRACE-FO uses a microwave ranging link—called the Microwave Instrument (MWI)—to determine the precise *separation distance* between two identical satellites orbiting Earth about 220 km (137 mi) apart at an initial altitude of approximately 490 km (305 mi). The MWI, using two frequencies at 24 GHz (K-band) and 32 GHz (K_a-band), is capable of measuring the distance between the two satellites to within one micrometer.

The changes in separation distance, tracked over time, can be used to create maps of Earth's gravity field at least every 30 days, which allows for tracking of changes in Earth's near-surface mass. In addition, each of the satellites will use GPS antennas to supply at least 200 profiles of atmospheric temperature distribution and water vapor content daily—see *Measuring Atmospheric Temperature and Humidity* on page 8 of this issue.

continued on page 2



The Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission launched onboard a SpaceX Falcon 9 rocket, Tuesday, May 22, 2018, at 12:47 PM PDT (3:47 PM EDT) from Space Launch Complex 4E at Vandenberg Air Force Base in California. **Photo credit:** NASA/Bill Ingalls

the earth observer

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Reminder: To view newsletter images in color, visit eosps.nasa.gov/earth-observer-archive.

GRACE-FO also tests a new experimental ranging technology that uses lasers instead of microwaves—called the Laser Ranging Interferometer (LRI). While the new technology provides a stepping stone to future missions, it also measures changes in the angle between the two spacecraft and thus enhances conventional microwave-ranging observations. Together, the very precise measurements of location, force, and orbital change translate into an observation of gravity with improved accuracy. Congratulations to the entire GRACE-FO team! Please turn to page 4 of this issue to learn more about the mission.

NASA is preparing to launch two instruments to the International Space Station (ISS) this year: the ECOSystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) and the Global Ecosystem Dynamics Investigation (GEDI, pronounced like "Jedi" of *Star Wars* fame).¹

ECOSTRESS was delivered to Kennedy Space Center on April 9, 2018, where it is in final preparations for launch to the ISS aboard the SpaceX-15 commercial resupply mission (CRS-15), currently scheduled to launch no earlier than June 28, 2018. ECOSTRESS will be robotically installed on the exterior of the station's Japanese Experiment Module-External Facility (JEM-EF) site 10 as soon as it arrives at the ISS.

¹ Both ECOSTRESS and GEDI were selected in 2014 as the winning proposals from the Earth Venture Instrument-2 (EVI-2) Announcement of Opportunity. Earth Venture is run by NASA's Earth System Science Pathfinder program, which oversees a portfolio of projects ranging from satellites, instruments on the space station, and suborbital field campaigns on Earth that are designed to be lower-cost and more focused in scope than larger, free-flying satellite missions.

ECOSTRESS is expected to provide key insights into how plants respond to heat and water stress by measuring *evapotranspiration* (ET).² These measurements allow scientists to understand the way in which plants respond to changing water availability. In addition, scientists hope to determine how changes in ET throughout the day affect plant growth.

In practical terms, the year of data anticipated from ECOSTRESS will also be useful for agricultural water managers. By working with the USDA and other partnering organizations, the ECOSTRESS team will advance our understanding of how key regions are affected by drought conditions and evaluate ways in which water management communities can make more efficient use of water resources for agriculture. The high spatial resolution of ECOSTRESS data will be particularly useful for research on the effects of drought on agriculture at the field-scale. While ECOSTRESS data will initially be used to address key ecosystem questions, they can also be used for a range of other applications such as studying volcanic activity, urban heat stress and heat waves, and surface temperature for ecosystem and resource management.

ECOSTRESS was built at and is managed by JPL, with **Simon Hook** serving as Principal Investigator (PI). To learn more about the current status of the mission as it prepares for launch, please see the News story on page 33 of this issue.³

² *Evapotranspiration* is the combined effects of *transpiration*, the process plants use to release water in order to regulate heat (similar to the way humans perspire) and *evaporation* of water from the soil.

³ To learn more about ECOSTRESS, visit <https://ecostress.jpl.nasa.gov>.

Meanwhile, GEDI is also now on an accelerated track for launch, after being moved from the SpaceX CRS-18 mission, which is now delayed to May 2019, to SpaceX CRS-16, which is currently scheduled for a November 2018 launch. The move to an earlier launch window is possible because the GEDI team's plan all along had been to have the GEDI instrument ready to launch by this fall. The lidar instrument is now undergoing final integration and testing at GSFC.

While NASA has flown multiple Earth-observing lidars in space (e.g., ICESat and CALIPSO) GEDI will be the first to provide high-resolution laser ranging of Earth's forests. Like ECOSTRESS, it will be robotically installed on the exterior of the station's JEM-EF site 6. That perch will be the perfect vantage point from which to measure the structure of Earth's tropical and temperate forests in high resolution and in three dimensions. These measurements will help fill in critical gaps in scientists' understanding of how much carbon is stored in the world's forests, the potential for ecosystems to absorb rising concentrations of CO₂ in Earth's atmosphere, and the impact of forest changes on biodiversity.

The University of Maryland, College Park is leading development of GEDI, with **Ralph Dubayah** serving as Principal Investigator; the instrument is being built at GSFC.⁴

Coincident GEDI and ECOSTRESS measurements provide a unique synergy to address ecosystem dynamics questions that cannot be answered using the instruments independently. The measurements from ECOSTRESS will provide information on the plant's function, evaporation, and its water-use efficiency. GEDI will provide information on the vegetation structure. Together these data can be used to obtain a better understanding of canopy functional traits and the global carbon sink potential. These data will be further complemented with data from two other instruments scheduled for launch to the ISS in 2019: NASA's Orbiting Carbon Observatory-3 (OCO-3) and the Japanese METI's Hyperspectral Imager Suite (HISUI). These instruments will collect information on vegetation functional traits and chemical composition through high-spectral-resolution measurements. Together these datasets will provide

⁴ To read a recent more detailed summary of the status of GEDI, see the "Summary of the Fourth GEDI Science Definition Team Meeting" in the March–April 2018 issue of *The Earth Observer* [Volume 30, Issue 2, pp. 17–19—https://eosps.nasa.gov/sites/default/files/2018/03/2018_color%20508_0.pdf]. There was also a more recent NASA press release available at <https://www.nasa.gov/feature/goddard/2018/may-the-forest-be-with-you-gedi-to-launch-to-iss>.

an unprecedented opportunity to better understand the Earth's vegetation.⁵

With regard to the status of ongoing missions, in our last issue, we reported that, on February 22, 2018, CloudSat successfully exited the Afternoon "A-Train" constellation via two thruster burns that placed the satellite in an orbit below the altitude of the A-Train and near the *CALIPSO graveyard orbit*—the orbit altitude that will be used by the CALIPSO spacecraft for eventual end-of-life operations.⁶ We are delighted to report that CloudSat resumed taking data in Daytime-Only Operations (DO-Op) mode from its new position on May 7, 2018. The satellite is successfully operating with three of four reaction wheels, and has full capability to make both large and small on-orbit maneuvers. The CloudSat and CALIPSO teams are discussing future operational plans, including an option for both CALIPSO and CloudSat to fly at the CALIPSO graveyard orbit and resume formation-flying under the A-Train. A decision has not yet been reached.

Last but not least, as it has done for the past six years, NASA participated in Earth Day activities held April 19–20 at Union Station in Washington, DC. This year's theme was *Amazing Technology*. The event featured 23 hands-on activities that ran the gamut from virtual reality experiences, to classifying coral using a touchscreen interface, to using a handheld spectrometer to test the reflectance of different vegetables. The centerpiece of the outreach, as it is with many NASA exhibits, was the Hyperwall—a nine screen, high definition video wall—where NASA's senior management, scientists, and outreach representatives delivered 40 multimedia stories over the course of the two-day event. Each story lasted about 15 minutes, covering a variety of Earth-science, heliophysics, planetary, and space-science topics. This was an extremely successful outreach event for NASA. Many thanks to all participants and the Science Communications Support Office for organizing this activity each year. Turn to page 13 of this issue to learn more about this year's Earth Day. ■

⁵ To learn more about the potential synergies between GEDI, ECOSTRESS, OCO-3, and HISUI, see the article by Stavros *et al.* in the June 22, 2017 issue of *Nature Ecology & Evolution*—<https://www.nature.com/articles/s41559-017-0194>.

⁶ To learn more, see "CloudSat Exits the A-Train" in the March–April 2018 issue of *The Earth Observer* [Volume 30, Issue 2, p. 4].

Note: List of undefined acronyms from the *Editor's Corner* and the *Table of Contents* can be found on **page 36**.

GRACE-FO: Tracking Earth's Mass in Motion

EDITOR'S NOTE: This feature content is taken from the GRACE-FO pre-launch mission brochure (https://eosps0.gsfc.nasa.gov/sites/default/files/publications/GRACE_FO%20Mission%20Brochure_508.pdf). While the intent is to reprint it with its original content largely intact, it has been modified slightly to match the style used in *The Earth Observer*, and to fit the layout space allocated for it.

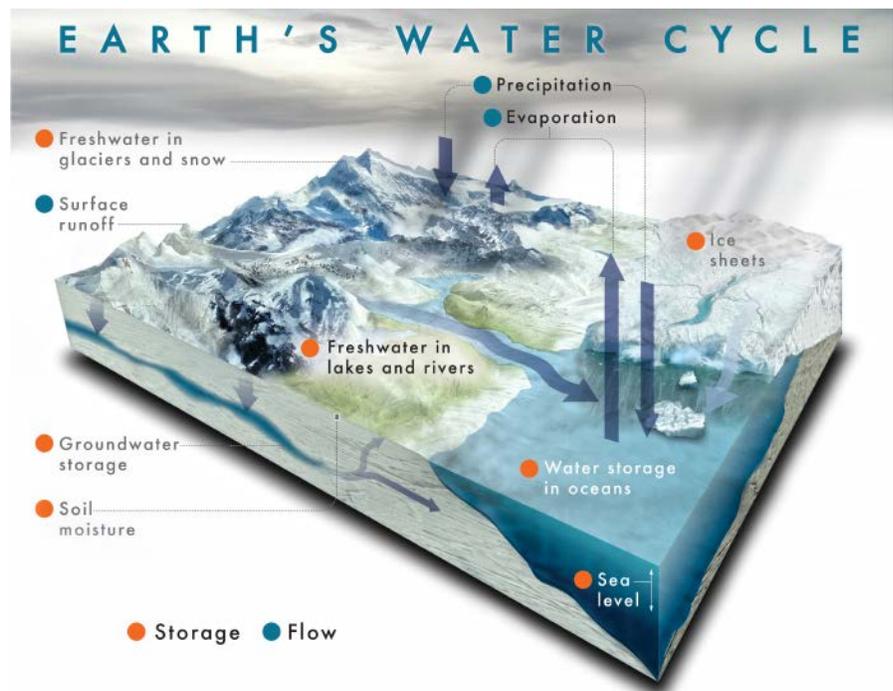
But regardless of whether water is solid, liquid, or vapor, visible or invisible, it has one attribute that does not change: its mass. Because everything that has mass inevitably has a gravitational pull associated with it, a unique twin satellite observing system has been used to measure the changing forces of gravity to track and follow Earth's water masses from the top of the Himalayas to the deepest ocean depths and deep underground.

Mass Transport and Gravity Change On Earth

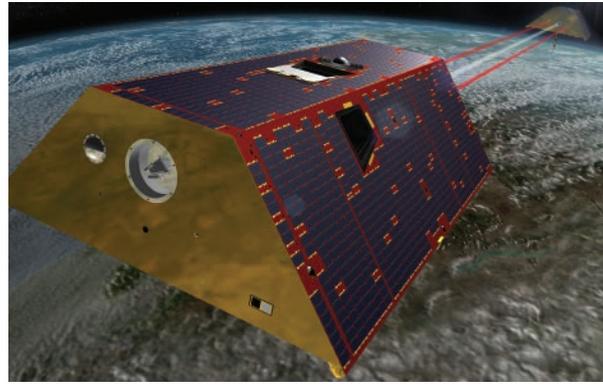
Panta rhei—"Everything flows." These famous words by the Greek philosopher Heraclitus express the truth that our complex world is ever changing and evolving. Even Earth's gravity field is continually changing. The pull of gravity varies naturally from place to place on Earth, depending on the mass distribution; greater mass exerts a stronger gravitational pull. But gravity also changes constantly as mass moves. While the masses of Earth's land features, such as mountains and valleys, change relatively slowly, the amount of water above, on, or below a particular location can vary seasonally, monthly, weekly, and even daily as water cycles between the subsystems (e.g., atmosphere, land, ocean, glaciers, polar ice caps, and underground).

On Earth, the processes that couple and transport water and energy are fundamental to today's most pressing climate science challenges. However, keeping track of Earth's evolving water system is a formidable task. Water constantly changes its shape, form, and state as it cycles between the ocean, atmosphere, and land—see **Figure 1**. It is in plain sight in lakes, rivers, and seas. It infiltrates the soil and groundwater. It accumulates on the ground as snow and can be stored as ice in glaciers and ice sheets, sometimes for hundreds and thousands of years. This makes it challenging to comprehensively observe and measure how much water cycles between Earth's subsystems. But regardless of whether water is solid, liquid, or vapor, visible or invisible, it has one attribute that does not change: its mass. Because everything that has mass inevitably has a gravitational pull associated with it, a unique twin satellite observing system has been used to measure the changing forces of gravity to track and follow Earth's water masses from the top of the Himalayas to the deepest ocean depths and deep underground. The measurements contribute to the assessment and monitoring of the Earth's heat and sea level budgets.

Figure 1. Changes in Earth's gravity field are due primarily to variations in water content as it moves through the water cycle—one of Earth's most powerful systems. Earth's gravity field is continually changing, mostly (but not solely) due to seasonal and climatic changes in water storage and flow. **Image credit:** NASA/JPL-Caltech



Given that the force of gravity is an ever-present driving force in the Earth system, it should come as no surprise that people have sought to describe and quantify its static component since ancient times. These efforts led to the development of the field of *geodesy*, the science branch that accurately measures the size and shape of Earth, defined by Earth's geometry and gravity field, and Earth's position and orientation in space. The field of geodesy took a major leap forward in 2002, when NASA and the German Aerospace Center (DLR) launched the Gravity Recovery and Climate Experiment (GRACE) satellite mission to map Earth's static gravitational field *and* how it changes from month to month. Circling the planet every 90 minutes for over 15 years at an altitude of 350-500 km (about 217-310 mi), the twin GRACE spacecraft closely tracked how their relative positions in space are affected by Earth's gravity.



Artist's conception of the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) satellites in orbit around the Earth. **Image credit:** NASA

GRACE's monthly maps of regional gravity variations provided new insights into how the Earth system functions and responds to change. Among its innovations, GRACE for the first time measured the loss of ice mass from Greenland and Antarctica—see **Figure 2**; improved our understanding of the processes responsible for sea level rise and ocean circulation; provided insights into where global groundwater resources may be shrinking or growing, where dry soils are contributing to drought and even forest fires; and monitored changes in the solid Earth (e.g., from earthquakes).¹ After more than 15 productive years in orbit—lasting three times longer than originally planned—the satellite mission ended science operations in late 2017. During its operation, GRACE provided truly global gravity measurements 100 times more accurate, and at spatial and temporal resolution higher, than had ever been achieved before from space, providing the much-needed measurements for characterizing how water is transported and cycled through the Earth system.

During its operation, GRACE provided truly global gravity measurements 100 times more accurate, and at spatial and temporal resolution higher, than had ever been achieved before from space, providing the much-needed measurements for characterizing how water is transported and cycled through the Earth system.

The GRACE Follow-On (GRACE-FO) mission will continue GRACE's legacy. Monitoring changes in ice sheets and glaciers, underground water storage, the amount of water in large lakes and rivers, and changes in sea level, provides a unique view of Earth's evolving climate as well as its water and energy cycles, with far-reaching benefits for its people. Measuring the redistribution and transport of mass around Earth is an essential observation for understanding current and future changes of the Earth's hydrosphere and its subcomponents.

¹To learn more, read "GRACE Mission: 15 Years of Watching Water on Earth" online at <https://gracefo.jpl.nasa.gov/news/117/grace-mission-15-years-of-watching-water-on-earth>.

GRACE Observations of Antarctic Ice Mass Changes

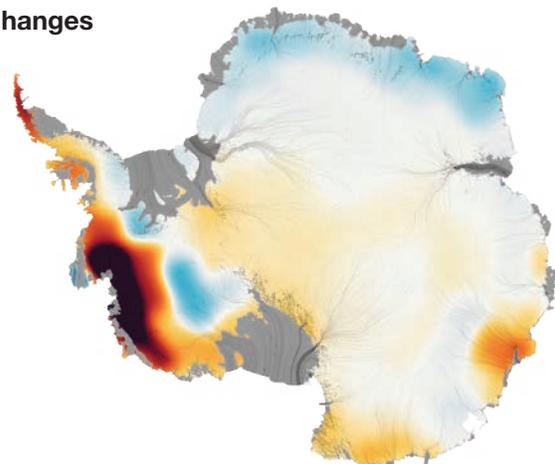
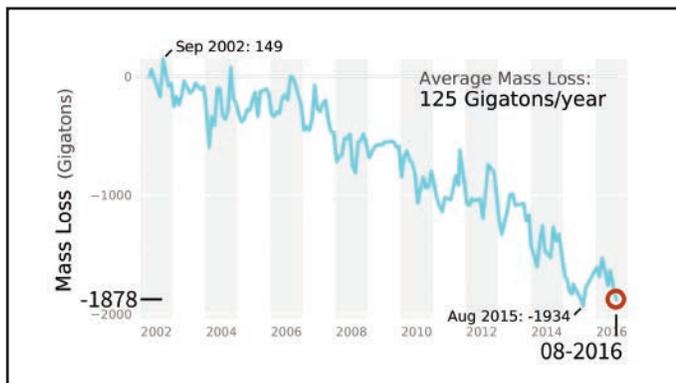
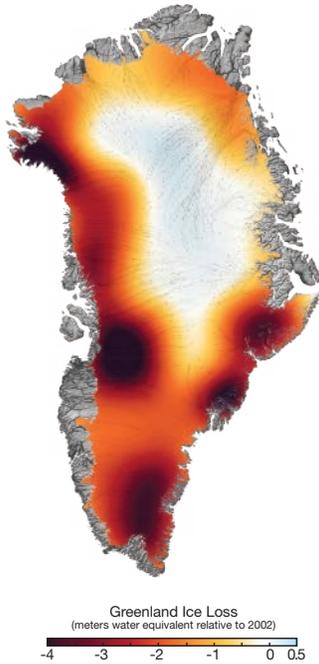


Figure 2. The mass of the Antarctic ice sheet has changed over the last several years. Research based on observations from GRACE indicates that between 2002 and 2016, Antarctica shed approximately 125 gigatons of ice per year, causing global sea level to rise by 0.35 mm (0.01 in) per year. **Image credit:** NASA/JPL-Caltech/University of California, Irvine

Antarctic Ice Loss (meters water equivalent relative to 2002)

The twin GRACE satellites, launched on March 17, 2002, have transformed scientists' view of how water moves and cycles between the ocean, land and atmosphere, and how water storage and availability are affected by droughts, floods, and human intervention.



The First GRACE Mission: A Legacy of Discoveries

"Revolutionary" is a word you hear often when people talk about the first GRACE mission. The twin GRACE satellites, launched on March 17, 2002, have transformed scientists' view of how water moves and cycles between the ocean, land, and atmosphere, and how water storage and availability are affected by droughts, floods, and human intervention.

In March 2017, GRACE celebrated the fifteenth anniversary of its launch. The discoveries achieved using GRACE data reflect the work of researchers worldwide, who have developed innovative techniques to use the data and combine them with other observations and models for new insights into complex Earth system processes, as well as for applications.

Melting Ice Sheets

Antarctica is one of the world's toughest places to collect data, and Greenland isn't far behind. Measuring how fast these ice sheets are melting is crucial to better understand rates and variations of sea level rise around the world. In the mid-2000s, GRACE data were used to clearly show that ice losses from Greenland and Antarctica were significantly larger than previous estimates from more indirect observations had suggested. Since GRACE launched, its measurements show Greenland has been losing about 280 gigatons of ice per year on average—see **Figure 3**—and Antarctica has lost approximately 125 gigatons a year with indications that both melt rates are increasing. To give perspective on how much water this is, a single gigaton of water would fill about 400,000 Olympic-sized swimming pools!

GRACE Observations of Greenland Ice Mass Changes

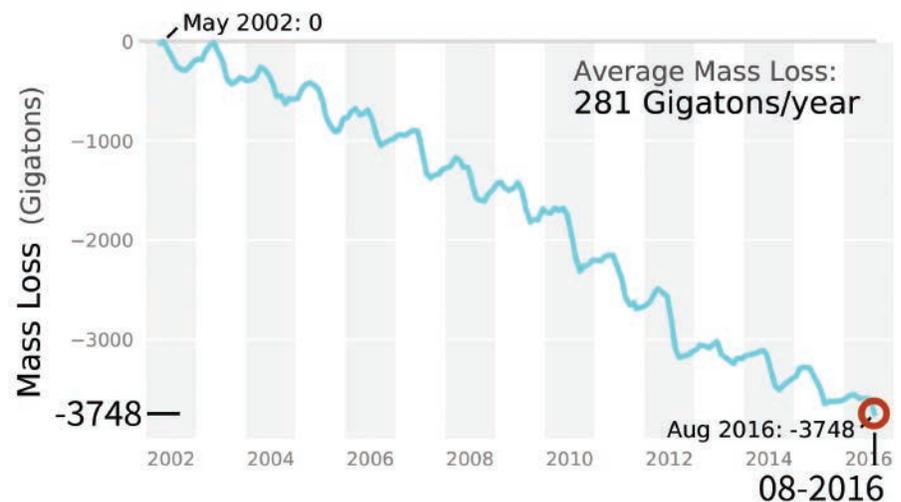
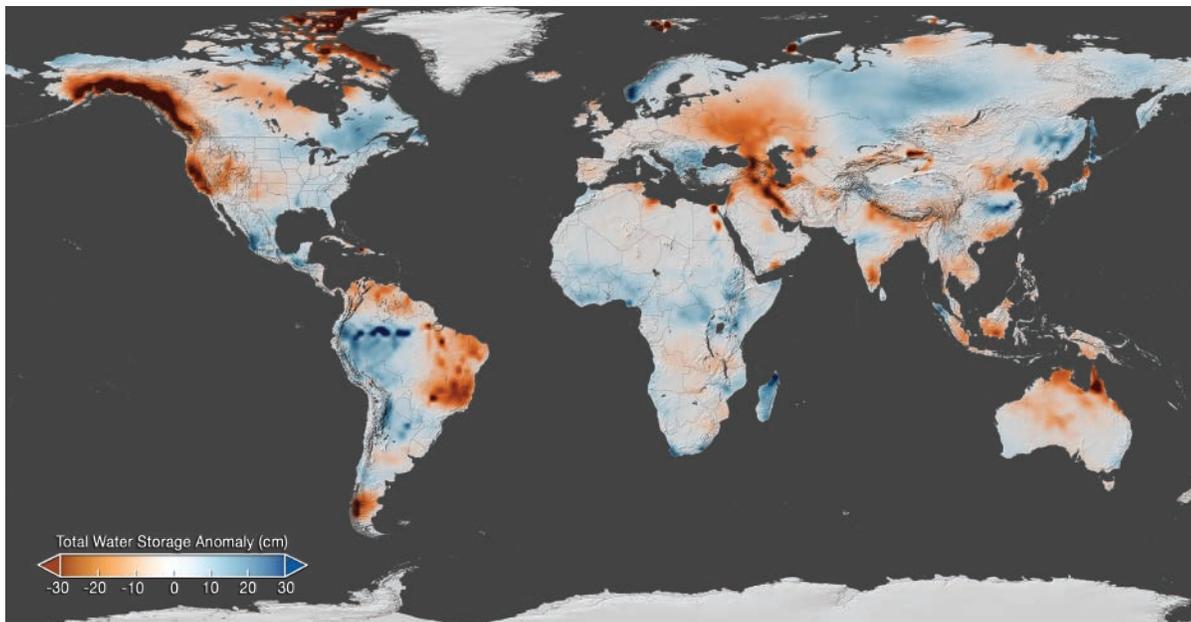


Figure 3. Research based on observations from the GRACE satellites indicates that between 2002 and 2016, Greenland shed approximately 280 gigatons of ice per year, causing global sea level to rise by 0.8 mm (0.03 in) per year. This image, created from GRACE data, shows changes in Greenland ice mass from 2002 to 2016. Darkest shades indicate areas that lost ice mass. The largest mass decreases of up to 30 cm (11.8 in) (equivalent-water-height) per year occurred along the West Greenland coast. **Image credit:** NASA

Underground Water

Water stored in soil and aquifers below Earth's surface is sparsely measured worldwide. Before GRACE, hydrologists were skeptical if they would be able to use the data to reveal unknown groundwater depletion. However, over the last decade, by measuring mass changes with GRACE, scientists from NASA and around the world have found more and more locations where humans are pumping out groundwater faster than it is replenished. For example, in 2015, a team of researchers published a comprehensive survey showing a third of Earth's largest groundwater basins are being rapidly depleted—see **Figure 4** on page 7. Adding the GRACE data to other existing sources of hydrological data has led to the development of a more efficient and sustainable approach to water management.



Dry soils can add to drought risk or increase the length of a drought. To help monitor these changes, NASA provided data on deep soil moisture and groundwater from GRACE to the National Drought Mitigation Center each week, using a hydrology model to calculate how the moisture was changing throughout the month between one map and the next. These data were used to prepare weekly maps of U.S. drought risk.

Sea Level

Sea level is rising because melting ice from land is flowing into the ocean and seawater is expanding as it warms. Since 1992, very precise, continuous measurements of sea level heights worldwide have been made by the NASA-Centre National d'Études Spatiales (CNES) Topography Experiment (TOPEX)/Poseidon mission and the successor Jason series of sea level altimetry missions. Altimeter measurements show how much sea level has risen, but not what causes it to rise—i.e., how much of the observed rise is from thermal expansion of seawater and how much is from increased volume due to ice melting and land runoff.

GRACE measured the monthly mass change of the ocean, and these data have enabled us to distinguish between changes in water mass and changes in ocean temperatures. An example of the value of this ability was a study that documented a sizable—if temporary—drop in sea level and linked it to changes in the global water cycle that was disrupted by the large La Niña event in 2011. The study showed that the water that evaporated from the warm ocean, causing the drop in sea level, was mostly rained out over Australia, South America, and Asia. The finding provided a new view into the dynamics and connections that shape the global water cycle.

Ocean Currents

When combined with measurements from sea-surface-height-measuring satellite altimeters, GRACE observations have greatly improved the precision of ocean current estimates. Beyond this classic application for ocean currents, GRACE observations have also directly been used to assess changes of large-scale current systems. At the bottom of the atmosphere—i.e., on Earth's surface—changes in air pressure (a measure of air's mass) tell us about flowing air, or wind. At the bottom of the ocean, changes in water pressure tell us about flowing water, or currents. A team of scientists at NASA developed a way to isolate the signal found in GRACE data indicating tiny pressure differences at the ocean bottom that are caused by changes in deep ocean currents. The measurements showed that a significant weakening in the overturning circulation, which a network of ocean buoys recorded in the winter of 2009-10, extended several thousand miles north

Figure 4. The gravity variations measured by GRACE can be used to determine water storage on land. By comparing current data to an average over time, scientists can generate an *anomaly map* to see where terrestrial water storage has decreased or increased. This map, created using GRACE data, shows the global terrestrial water storage anomaly in April 2015, relative to the 2002-2015 mean. Rust colored areas show where water has decreased, and areas in blue are where water levels have increased. The significant decreases in water storage across most of California are related to groundwater, while decreases along the Alaska coastline are due to glacier melt. **Image credit:** NASA's Scientific Visualization Studio

GRACE-FO Mission Objectives

The primary objective is to continue the high-resolution monthly global maps of Earth's gravity field and surface mass changes of the original GRACE mission over a period of five years.

The secondary objectives are to demonstrate the effectiveness of a novel Laser Ranging Interferometer (LRI) in improving the Satellite-to-Satellite Tracking (SST) measurement performance, laying the groundwork for improved future space-gravimetry missions. GRACE-FO will also continue measurements of radio occultations for operational provision of vertical atmospheric temperature and humidity profiles to weather services.

and south of the buoys' latitude near 26° N. The new measurements from GRACE agreed well with estimates from the buoy network, confirming that the technique can be expanded to provide estimates throughout the Atlantic and beyond. Because ocean currents distribute heat across the planet, any changes in ocean currents are important indicators of how our planet is responding and evolving in a warming climate.

Solid Earth Changes

The viscous mantle under Earth's crust is also moving ever so slightly in response to mass changes from water near the surface. GRACE has a community of users that seek to quantify these shifts. Scientists at NASA used GRACE data to calculate how ice sheet loss and groundwater depletion have actually changed the rotation of Earth as the system adjusts to these movements of mass. Like a spinning top, any change in the distribution of mass will cause Earth's axis to shift, wobble, and readjust. GRACE helps to pinpoint those rotation changes and understand their causes.

In addition, some large earthquakes move enough mass for GRACE to detect. During 15 years in orbit, GRACE was able to measure the instantaneous mass shifts from several large earthquakes and monitor the large but slow tectonic mass adjustments that go on for months and even years after an earthquake. These measurements provide unprecedented insights into what is happening far below Earth's surface during and after big quakes, such as the 2004 Sumatra event and 2011 Tohoku (Japan) quake, both of which caused devastating tsunamis.

GRACE Follow-On: Mission Overview

The GRACE Follow-On joint mission by NASA and the German Research Centre for Geosciences (GFZ) will continue the successful GRACE data record. The GRACE-FO mission builds on and extends the capabilities of its predecessor, and also includes an experimental instrument that promises to be more accurate and allows for the detection of even smaller gravitational signals—see *GRACE-FO Mission Objectives*. In orbit, the twin satellites will provide accurate measurements of changes in Earth's gravitational field at least every 30 days, and allow for the tracking of changes and redistribution in Earth's near-surface mass. In addition, each of the satellites will use global positioning system (GPS) antennas to supply at least 200 profiles of atmospheric temperature distribution and water vapor content daily—see *Measuring Atmospheric Temperature and Humidity*.

Like its predecessor, the GRACE-FO mission consists of two identical satellites orbiting Earth at about 220 km (137 mi) apart at an initial altitude of approximately 490 km (305 mi). One of the unique aspects of GRACE and GRACE-FO is that the satellites themselves are effectively the “instruments.” Unlike other Earth-observing satellites equipped with instruments pointing down at Earth's surface, the GRACE-FO satellites instead “look” at each other. Together, they represent a single measurement system.

Measuring Atmospheric Temperature and Humidity

While the main global positioning system (GPS) receivers on the first GRACE mission were used for precise orbit determination, a set of secondary GPS antennas measured the bending of the signals between GRACE and GPS satellites that were low over the horizon. This way, the GPS signals graze and pass through Earth's atmosphere—known as *occultation*. The GPS radio waves are altered slightly as they pass through the atmosphere due to refractive effects, and these changes can be analyzed to create atmospheric profiles including refractivity, temperature, pressure, and humidity. Radio occultation measurements complement and continue a long series of similar data obtained by sensors on other satellites and are very useful for weather forecasting and climate studies.

GRACE-FO will provide at least 200 daily near-real-time occultation observations from each satellite—data that are used operationally worldwide by leading weather centers to improve global weather forecasts. Over longer time scales, the GPS radio-occultation data are contributing to climate variability studies.

One satellite will follow the other along the same polar orbit, with both continually sending ranging signals to each other and carefully tracking any changes in the distance between the two satellites. When the GRACE-FO satellites encounter a change in the distribution of Earth's mass—such as a mountain range or reduced mass of underground water—the distance between the two satellites will change—see **Figure 5**. By precisely and continuously tracking this change to within a fraction of the thickness of a human hair during each orbit every month, regionally and temporally varying gravity changes can be measured with high precision.

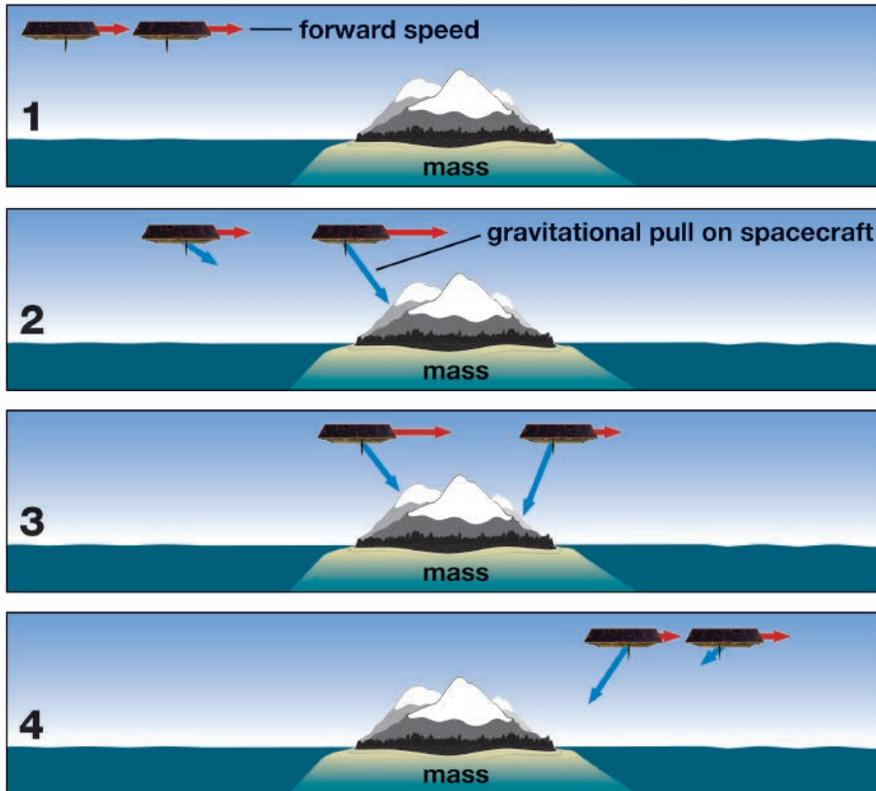


Figure 5. How GRACE-FO Works. This simplified example illustrates the movements of the satellites as they pass southward from the Caribbean Sea across Colombia and Peru (i.e., a denser landmass) to the Pacific Ocean. The two satellites begin over the ocean (*Panel 1*), but when the leading spacecraft encounters land, the land's higher gravity pulls it away from the trailing spacecraft, which is still over water (*Panel 2*). Once the second satellite encounters the land, it too is pulled toward the mass and consequently toward the leading spacecraft (*Panel 3*). When the lead spacecraft moves back over water, it is pulled back slightly by the land, while the trailing spacecraft continues over the land. Once both spacecraft are back over water, the trailing spacecraft is slowed by the land (*Panel 4*) before returning to its original distance behind the leading spacecraft. **Image credit:** NASA

GRACE-FO will be able to make accurate measurements, thanks in part to the innovative use of two technologies: a *microwave ranging system* based on GPS technology, and a very sensitive *accelerometer*—an instrument that measures the forces on the satellites besides gravity (e.g., atmospheric drag or solar pressure). GRACE-FO will use the same two-way microwave-ranging link as GRACE, called the Microwave Instrument (MWI). The MWI operates using two frequencies—at 24 GHz (K-band) and 32 GHz (K_a -band)—and is capable of measuring the distance between the two satellites to within one micron—about the diameter of a blood cell, or a small fraction of the width of a human hair. This allowed the GRACE satellites to detect gravitational differences on the planet's surface with a precision equivalent to a change of 1 cm (0.4 in) in water height across areas of about 340 km (approximately 211 mi) in diameter.

With the same kind of microwave ranging system, GRACE-FO satellites can expect to achieve a similar level of inter-satellite ranging precision. But they will also test and demonstrate an experimental instrument using lasers instead of microwaves, which promises to improve the precision of the separation distance measurements on future generations of GRACE satellites by a factor of about 20, thanks to the laser's higher frequencies. The instrument, developed jointly between NASA's Jet Propulsion Laboratory, the Max Planck Institut für Gravitationsphysik (Germany), and GFZ, is called the Laser Ranging Interferometer (LRI)—see **Figure 6**. The LRI is a stepping

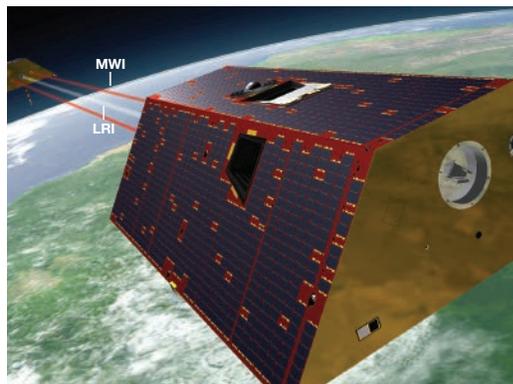


Figure 6. The experimental Laser Ranging Interferometer (LRI) is expected to provide better ranging precision than GRACE's MWI system. LRI is being tested on GRACE-FO as an enabling technology for the next generation of mass-change missions. **Image credit:** NASA

GRACE-FO at a Glance	
Size (of each satellite)	1.94 m wide, 3.12 m long, 0.72 m high
Mass	600 kg
Power	Solar cells
Altitude	490 ± 10 km
Velocity	~7.5 km/sec
Inclination	89°
Orbit	Polar orbit
Orbit Duration	90 minutes
Orbits Per Day	~15
Design Life	5 years
Fuel Life	>5 years

stone for future missions to enhance gravity measurements. It will also measure changes in the angle between the two spacecraft and thus support the conventional microwave-ranging observations. Together, the very precise measurements of location, force, and orbital change translate into an observation of gravity with improved accuracy.

Spacecraft Design and Launch

The GRACE-FO satellites follow the successful design of the original GRACE spacecraft. Each identical satellite is 1.94 m (6.36 ft) wide, 3.12 m (10.25 ft) long, and 0.72 m (2.36 ft) high, with a mass of 600 kg (1,323 lbs). Both spacecraft are covered in solar panel arrays that power the satellites.

The GRACE-FO satellites will be launched together from Vandenberg Air Force Base in California into Earth orbit on a SpaceX Falcon 9 launch vehicle as a shared ride with five communications satellites. The GRACE-FO satellites will be deployed first from the launch vehicle into a low-Earth, near-polar orbit, after which the launch vehicle will continue on to a higher orbital altitude before releasing the communications satellites.

The GRACE-FO twin satellites, after release at an altitude of about 490 km (305 mi), will be maneuvered to a separation distance of about 220 km (137 mi) apart. As the satellites circle Earth, the ranging technology will measure separation between the satellites at the micrometer level, and the GPS sensor will provide the location of the satellites in their orbits. These observations will then be combined and processed using supercomputers to estimate month-to-month gravity and surface mass variations.



GRACE-FO launched aboard a SpaceX Falcon 9 from Vandenberg Air Force Base in California on May 22, 2018. Pictured here on the Vandenberg launch pad is a Falcon 9 rocket with the Jason-3 satellite onboard. **Photo credit:** NASA/Shiflett



The GRACE-FO satellites were assembled by Airbus Defence and Space in Germany with major components from a number of countries including Denmark, England, France, Germany, Italy, Sweden, and the U.S. This photo shows the satellites inside the IABG testing facility in Munich, Germany. **Photo credit:** Airbus DS Industrieanlagen-Betriebsgesellschaft GmbH-A.Ruttloff

Ground System and Data Products

The GRACE-FO mission ground system includes all the assets needed to command and operate the twin satellites in orbit, as well as manage, process, and distribute their data—see **Figure 7**.

To communicate with the satellites, the German Space Operations Center (GSOC) in Oberpfaffenhofen (Germany) sends commands through ground stations in Weilheim or Neustrelitz (Germany) directly to the GRACE-FO satellites. Once data have been collected onboard the spacecraft, they are transmitted to the two German stations or to the GFZ station in Ny-Ålesund (Norway). From there, all received telemetry is sent to the Raw Data Center (RDC) in Neustrelitz, and to the Physical Oceanography Distributed Active Archive Center (PO.DAAC) at JPL in Pasadena, California, as well as to the Information System and Data Center (ISDC) at GFZ in Potsdam (Germany), and the University of Texas Center for Space Research (UT-CSR) for monitoring and further analysis. GSOC provides real-time monitoring of the spacecraft status and functions, and will send new software commands as necessary for optimal operations. Data from the GRACE-FO satellites are returned every 96 minutes.

These data will inform hydrologists about up-to-date land water storage conditions, provide glaciologists with accurate measurements of glacier and ice sheet mass changes, allow oceanographers to assess global and regional sea level and ocean current variations, among other uses. Data from GRACE-FO are expected to provide new perspectives of Earth's ever-changing water cycle that will benefit society for years to come—see *Applications and Benefits to Society* on page 12. Once GRACE-FO is fully operational, high-resolution, monthly global models of Earth's gravity field will be freely available at <http://grace.jpl.nasa.gov/data>.

High-resolution, monthly global models of Earth's gravity field will be freely available at <http://grace.jpl.nasa.gov/data>.

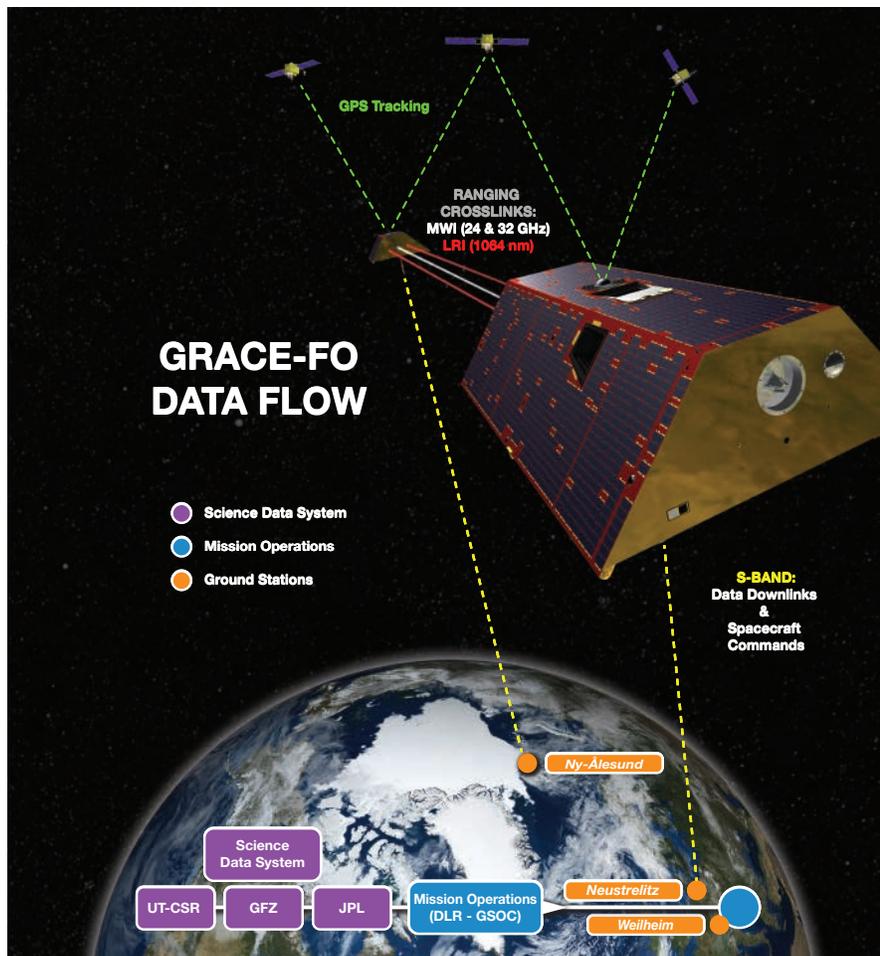


Figure 7. This graphic shows how data travel from the GRACE-FO satellites to receivers on the ground. The measurement and housekeeping data are stored onboard the GRACE-FO satellites and relayed to ground stations when the satellites pass over at least once a day. **Image credit:** NASA

“GRACE was a pioneering mission that advanced our understanding across the Earth system—land, ocean, and ice. The entire mission team was creative and successful in its truly heroic efforts over the last few years, extending the science return of the mission to help minimize the gap between GRACE and its successor mission, GRACE Follow-On.”

—**Michael Watkins**
Director of NASA’s Jet Propulsion Laboratory and GRACE-FO’s Science Team Lead

“GRACE-FO allows us to continue the revolutionary legacy of GRACE. There are sure to be more unexpected and innovative findings ahead.”

—**Frank Webb**
Project Scientist for GRACE-FO at NASA’s Jet Propulsion Laboratory

Applications and Benefits to Society

Among the applications of GRACE-FO mission data are improvements to our understanding and forecasting of freshwater availability, droughts, agricultural resources, sea level rise, climate change, and solid Earth changes. Data from GRACE-FO—along with information from other Earth-observing satellites and airborne missions, combined with ground-based data—will lead to advances in Earth system science for years to come.

Monitoring Freshwater Resources

Water resource managers rely on accurate estimates of underground water storage like those provided by GRACE and soon GRACE-FO to monitor freshwater resources necessary for human activities including public consumption, irrigation, and sanitation—among other uses.

Enhanced Prediction Skills for Weather and Climate

By providing GPS radio-occultation measurements daily, coupled with an improved understanding of the global water cycle, data from GRACE-FO will help advance Earth system analysis and weather and climate modeling.

Improved Forecasting Capabilities for Drought and Flood Risk

Too much or too little water can have huge impacts on people around the world. The agricultural community, wildfire managers, and other decision-makers will use GRACE-FO data to provide weekly maps of drought risk.

Improved Predictions of Flood Potential

GRACE-FO will provide a means to observe monthly variations in total water storage within large river basins. The terrestrial water storage signal defines the time-variable ability of land to absorb and process water, and accounts for the water beneath the surface. Water storage information from GRACE-FO will allow users to assess the predisposition of a river basin to flooding as much as 5–11 months in advance.

Improved Sea Level Change Prediction and Ocean Current Monitoring

Data from GRACE-FO will allow scientists to keep a close eye on sea level and determine—in conjunction with other observations—how much of the change is due to warming, ice melting, or runoff from land. Ocean bottom pressure measurements from GRACE-FO will also enable the tracking of deep ocean current changes.

Better Solid Earth Monitoring

Data from GRACE-FO will also record mass changes originating from earthquakes, tsunamis, volcanic eruptions, and the Earth’s crust as it adjusts to other mass changes such as loss of land ice. This effectively provides a window into the interior of our planet, and gives researchers new data to infer material properties deep below the surface.

Conclusion

Changes in how mass is distributed within and between Earth’s atmosphere, oceans, groundwater, and ice sheets are fundamental indicators of the large-scale dynamics of the planet. For more than 15 years, NASA’s GRACE mission monitored mass changes every month with far-reaching impact on our understanding of the Earth system and how it is evolving. GRACE-FO continues the legacy of GRACE, tracking Earth’s water movement and surface mass changes across the planet. Monitoring changes in ice sheets and glaciers, near-surface and underground water storage, the amount of water in large lakes and rivers, as well as changes in sea level and ocean currents, provides an integrated global view of how Earth’s water cycle and energy balance are evolving—measurements that have important implications for everyday life. ■

Celebrating Earth Day with NASA: “The Best Day Ever!”

Heather Hanson, NASA's Goddard Space Flight Center, Global Science and Technology, Inc., heather.h.hanson@nasa.gov

Introduction

With more than seven billion people onboard, Earth is the only planet in the universe known to support life. It may therefore be thought of as a huge, populated spacecraft. Consequently, NASA's scientists and engineers work tirelessly to advance our scientific understanding of Earth as a system and its responses to natural and human-induced changes, to better keep all systems “Go!”

In recognition of its unique status, people around the world have celebrated Earth Day for nearly 50 years. While there is a sense that “every day is Earth Day,” i.e., environmental stewardship and protection should be a priority every day, April 22 has been set aside to specifically focus on these themes.

Explaining the design inspiration for the 2018 NASA Science Earth Day poster, **Jenny Mottar** [NASA Headquarters—*Science Mission Directorate Art Director*] states that, “Earth is really the best seat in the universe,”—see **Figure 1**. In fact, to our knowledge it is the *only* seat in the universe—and therefore on Earth Day should be celebrated in true NASA fashion.

Celebrating Earth Day with NASA

Organized by NASA's Science Communications Support Office, NASA held its sixth annual Earth Day celebration at Union Station in Washington, DC, on April 19-20. The two-day event, which was free and open to the public, took place inside Union Station's historic (and newly renovated) Main Hall¹—see **Photo 1**. This central transportation hub attracts some 25,000 to 30,000 people daily, allowing NASA potentially to reach a larger group of citizens than those who were already planning to attend the event.

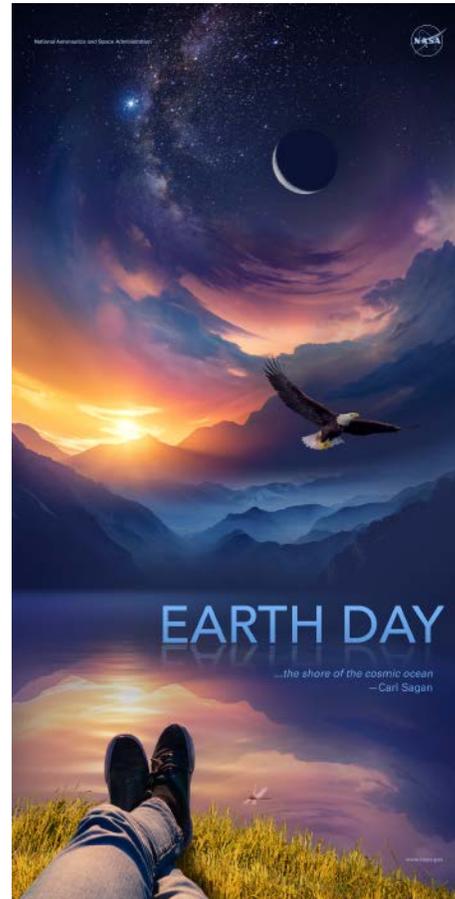


Figure 1. The 2018 NASA Science Earth Day poster.
Credit: Jenny Mottar, NASA



Photo 1. NASA science activities as seen from a balcony above Union Station's Main Hall. The Hyperwall was the centerpiece of the exhibit.
Photo credit: NASA

¹ Union Station's Main Hall has now been fully restored nearly five years after a magnitude 5.8 earthquake hit the DC region.

This year's NASA Earth Day theme was *Amazing Technology*.

This year's NASA Earth Day theme was *Amazing Technology*. The exhibit featured 23 hands-on activities that ran the gamut from virtual reality experiences, to classifying coral using a touchscreen interface, to using a handheld spectrometer to test the reflectance of different vegetables—see **Table 1** for a listing of all the activities.

Table 1. Hands-On Activities at NASA's 2018 Earth Day celebration.

Activity Title	Description
What's Binary Code?	To process and store data, computers use a simple coding system, called binary code. In this activity participants used different-colored beads to encode the initials of their first and last names.
Ultraviolet Beads	NASA keeps a close eye on the sun's ultraviolet (UV) radiation. Participants became UV detectives, using specially designed UV-sensitive beads. They walked away with their very own UV-detection bracelet.
Ocean Life from Space	Our "blue ocean" is actually made up of a broad spectrum of colors, depending on the changing locations of microscopic life in it. Differences in ocean color are visible from space, thanks to NASA's satellite technologies. Participants examined how NASA detects ocean life and took a selfie with their "Best Phyto Friend Forever" (BPF).
Earth Observatory for Kids	<i>EO Kids</i> is committed to making Earth science fun and engaging by bringing NASA Earth Observatory (EO) stories and NASA Earth science data to a younger audience (ages 9–14). Participants learned about topics in Earth science from a satellite perspective, and engaged in fun-filled, hands-on activities on a personal level.
Exploring Earth's Neighbor: The Moon	Our moon is a stunning and beautiful place! Participants examined how it's similar to—and yet quite different from—Earth.
Spectral Measurements: The World's Fingerprints	Participants learned how NASA's satellites use spectrometers to measure the differing amounts of light wavelengths reflected off Earth's surface. They tested their skill at matching such spectral signatures with features in satellite images.
Spectral Measurements, Plant Health, and Your Health!	Satellite observations can monitor the health of plants by measuring multiple wavelengths of reflected light. These observations provide scientists with data to help predict when and where crops are at risk from drought, floods, and even air pollution. Participants learned how NASA is keeping an eye on our world's food supply from space.
Finding an Earth-Like Planet Light Years Away	Participants learned how scientists use a technique called <i>transit spectroscopy</i> to discover and characterize planets outside of our solar system (called <i>exoplanets</i>) as they search for other Earth-like planets in the universe.
The Notion of Ocean Motion	In this activity, participants explored how water moves through the ocean. By observing what happens when fresh water is poured on top of salt water in a tube, they learned how fluids move depending on their densities.
Mapping Temperature, Pressure, and Humidity of the Earth	Participants learned why mapping profiles of temperature, pressure, and humidity of the atmosphere around the globe (using a technique called <i>sounding</i>) is important to weather forecasting.
Sky View/Ground View with GLOBE	NASA satellite observations of the Earth's environment need to be complemented with observations made on the ground. Participants learned how they can make citizen-science, ground-based observations, and got a chance to see an augmented-reality view of satellite imagery of our planet.
Clouds and Earth's Radiant Energy Budget	Do clouds affect the temperature and atmosphere of Earth? Participants explored two environments—one with clouds and one without—to learn how clouds affect Earth's temperature.
Seeing in the Dark	When a huge chunk of ice, known as Iceberg A-68, broke off the Larsen C ice shelf in 2017 NASA was able to observe it. How was that possible? Participants explored how the thermal imager on the Landsat satellite can reveal breaks, or rifts, in the ice shelves and provide valuable insight into how the Earth's cryosphere is changing.

Table 1. (cont.) Hands-On Activities at NASA's 2018 Earth Day celebration.

Activity Title	Description
Magnetic Earth, Magnetic Sun, and Virtual Reality	Participants viewed a NASA satellite in virtual reality and learned about magnetism in the sun–Earth system.
The Earth and Titan: Greenhouse Cousins	One of Saturn's moons, Titan, has many similarities to Earth, including an atmosphere with clouds and rain. The difference is that Titan is so cold that what rains is liquid methane—not water! Participants learned how the greenhouse effect on both worlds acts like a blanket to warm the surface.
Lasers, Bouncy Balls, and the ICESat-2 Mission	Scheduled to be launched in September 2018, NASA's ICESat-2 mission will measure the varying height of the surface of our planet, one laser pulse at a time. Participants learned about the ICESat-2 mission, lasers, and tried out the ICESat-2 Bouncy Ball Photon-Counting Challenge.
Measuring Precipitation from Space	Participants learned the nuts and bolts about how and why NASA's satellites measure precipitation from space.
Future Tech for Earth Science	NASA is building new technologies today that will help us see Earth like never before. Participants could see models of tiny satellites and smart sensors either already in space or planned for launch in the near future.
NeMO-Net: Drones That See Through Ocean Waves	Participants played an interactive, game-based feature to map our planet's coral-reef ecosystems. NeMO stands for New Millennium Observatory.
B-Line to Space	Up, up, and away! Participants learned how NASA's balloons are used to understand the dynamics of Earth's atmosphere.
View Your World with NASA Worldview	Participants used NASA's Worldview digital tool to explore and visualize Earth science data and explore natural hazards.
Dynamic Planet	This touchscreen interface allowed participants to drive a spherical display that showed a variety of remote-sensing satellite datasets.
Digital Photo Booth	Participants could walk away with a free photo of themselves superimposed on an astronaut spacesuit.

Participants were given an *activity passport* that listed the 23 activities to choose from; after completing at least 6 activities (see **Photos 2 - 7**), they could turn in their passport to redeem a special NASA-provided take-home kit (i.e., a NASA drawstring bag with some outreach materials of their choosing).

Participants were given an activity passport that listed the 23 activities to choose from.



Photo 2. Participants at the *Sky View/Ground View with GLOBE* activity used augmented reality goggles to view satellite imagery of our planet. **Photo credit:** NASA



Photo 3. Participants at the *NeMO-Net: Drones That See Through Ocean Waves* activity used a touchscreen video-game table to classify different types of coral reef systems. **Photo credit:** NASA



Photo 4. Participants at the *Spectral Measurements, Plant Health, and Your Health!* activity used a handheld spectrometer to test the reflectance of different types of lettuce. **Photo credit:** NASA



Photo 5. Participants at the *Seeing in the Dark* activity moved chunks of ice around in a large plastic tub of water while viewing temperature differences via an infrared camera's image projected on an iPhone. **Photo credit:** NASA



Photo 6. Participants at the *Lasers, Bouncy Balls, and the ICESat-2 Satellite Mission* activity released bouncy balls in a cardboard box to demonstrate the laser technology used on the ICESat-2 mission—scheduled to launch in 2018. **Photo credit:** NASA



Photo 7. Participants at the *B-Line to Space* activity got an up-close-and-personal view of a NASA balloon used to study the atmosphere. **Photo credit:** NASA

*The centerpiece of the NASA experience was the **Hyperwall**—a nine-screen, high-definition video wall—where NASA's senior management, scientists, and outreach representatives delivered 40 multimedia stories over the course of two days.*

The centerpiece of the NASA experience was the *Hyperwall*—a nine-screen, high-definition video wall—where NASA's senior management, scientists, and outreach representatives delivered 40 multimedia stories over the course of two days. Each story lasted about 15 minutes, covering a variety of Earth-science, heliophysics, planetary, and space-science topics. The exhibit also featured an Explorer 1 “selfie station,” where participants could hold up a paper cutout of the Explorer 1 spacecraft—the first satellite launched by the U.S., on January 31, 1958—to recreate a scene similar to the one captured in a photograph of three men responsible for the success of Explorer 1—see **Photos 8** and **9**. Participants also had a unique opportunity to take photos of Union Station's K9, *Summer*, who helps keep Union Station a safe venue—see *A War Dog Visits Earth Day* on page 20.

On the first day of the event and as arranged earlier, more than 350 middle- and high-school students from schools in Maryland, Virginia, and the District of Columbia, joined the general public to attend the event. The students and general public gathered in front of the Hyperwall for opening remarks at 10:30 AM—see **Photo 10**. To kick off the event, **Michael Freilich** [NASA Headquarters—*Director of the Earth Science Division*] explained how aliens coming into our solar system might first be drawn to the larger planets such as Jupiter and Saturn, but they'd soon home in on Earth—the only planet visibly teeming with life. Freilich briefly explained how NASA uses the vantage point of space to study and monitor our planet, collecting important measurements that impact our daily lives (e.g., weather forecasts). Former NASA Astronaut **Paul Richards** spoke next. Richards reminisced about orbiting Earth in Space Shuttle *Discovery*, including trips to the International Space

Station. He explained that similar to his experience as a NASA astronaut, we are all astronauts onboard Spaceship Earth—and we must take care of our “spacecraft,” as there is no backup “Planet B” if we needed one to continue our existence. Next, **Brent Reetz** [Union Station—*Senior General Manager*] and **Nzinga Bryant** [Union Station Redevelopment Corporation—*Vice President and Director of Finance and Administration*] gave welcoming remarks, emphasizing the station’s green initiatives and recycling efforts.

Following the kick-off presentation, the students were divided into small groups that followed a rotation schedule that would allow every student access to various activity centers with minimum confusion. Each group completed several of the 23 hands-on activities and listened to a variety of multimedia stories at the Hyperwall, including a presentation titled *Viewing Earth from Space: An Astronaut’s Perspective*, given by Former NASA Astronaut **Paul Richards**, where all 350 participants gathered in front of the Hyperwall. To view the list of Hyperwall stories from the first day, see **Table 2** on page 18. In addition to the hands-on activities and Hyperwall stories, Paul Richards held a one-hour autograph signing that was open to the public on April 19—see **Photo 11**. Approximately 1000 other visitors to the station participated in NASA’s activities on that day.

He explained that similar to his experience as a NASA astronaut, we are all astronauts onboard Spaceship Earth—and we must take care of our “spacecraft,” as there is no backup “Planet B” if we needed one to continue our existence.



Photo 8. Pictured here are three men responsible for the success of Explorer 1, America’s first Earth satellite, launched January 31, 1958. At left is William H. Pickering, former director of NASA/Jet Propulsion Laboratory, which built and operated the satellite; at center is James A. Van Allen, of the State University of Iowa, who designed and built the instrument that discovered the now-well-known radiation belts which circle the Earth; and at right is Wernher von Braun, leader of the Army’s Redstone Arsenal team that built the first-stage Redstone rocket that launched Explorer 1. **Credit:** NASA



Photo 9. Students recreated the Explorer 1 photograph of three men responsible for the success of Explorer 1. **Photo credit:** NASA



Photo 10. Participants gathered in front of NASA’s Hyperwall for a special kickoff celebration. Left to right: **Michael Freilich**, Former NASA Astronaut **Paul Richards**, **Brent Reetz**, and **Nzinga Bryant**. **Photo credit:** NASA



Photo 11. Former NASA Astronaut **Paul Richards** held a one-hour autograph signing—open to the public—on Thursday, April 19. **Photo credit:** NASA

Table 2. Hyperwall stories from day one of NASA's Earth Day celebration.

Presentation Title	Presenter [Affiliation]
Celebrating Earth	Brian Campbell [NASA's Wallops Flight Facility (WFF)]
Opening Remarks to Kickoff Earth Day 2018	Michael Freilich [NASA Headquarters (HQ)— <i>Director of the Earth Science Division (ESD)</i> Former NASA Astronaut Paul Richards Brent Reetz [Union Station— <i>Senior General Manager</i>] Nzinga Bryant [Union Station Redevelopment Corporation— <i>Vice President and Director of Finance and Administration</i>]
Looking Down on the Earth: Satellites, Science, and Societal Benefit	Michael Freilich [NASA HQ— <i>Director of the ESD</i>]
Earth's Biodiversity: The View from Space	Allison Leidner [NASA HQ]
NASA's Black Marble: Striking Images of Earth at Night	Miguel Román [NASA's Goddard Space Flight Center (GSFC)]
Viewing Earth from Space: An Astronaut's Perspective	Former NASA Astronaut Paul Richards
Can We Really See Landslides from Space?	Dalia Kirschbaum [GSFC]
From Space to Society: Solving Practical Problems on Earth	Stephanie Uz [GSFC]
Calling All Cloud Gazers: NASA Needs Your Help!	Kristen Weaver [GSFC]
SERVIR: Connecting Space to Village	Dan Irwin [NASA's Marshall Space Flight Center]
Shoot for the Stars No Matter the Odds	Hakeem Oluseyi [NASA HQ]
Sunny with a Chance of Solar Storms	C. Alex Young [GSFC]
Walking On Other Worlds Without Leaving Earth	Jacob Richardson [GSFC]
Protecting the Earth: NASA's Planetary Defense Program	Michelle Thaller [NASA HQ— <i>Deputy Director for Communications, Science Mission Directorate</i>]
Watching Icebergs Break Away from Antarctica with Landsat	Christopher A. Shuman [University of Maryland Baltimore County's Joint Center for Earth Systems Technology (JCET) at GSFC]
Tracking Water from Space with NASA's Gravity Satellite Missions	Bryant Loomis [GSFC]
Satellites, Ships, Shoes: Observing the Living Ocean from Above	Jeremy Werdell [GSFC]
Drones that See Through Waves: New Marine Sensing Technologies	Ved Chirayath [NASA's Ames Research Center, Laboratory for Advanced Sensing]
Watching the Earth Breathe Through Satellites and Models	Lesley Ott [GSFC]
Titan and Earth: Climate Cousins	Conor Nixon [GSFC]
ICESat-2: Space-Borne Lasers that Measure the Polar Ice Caps	Valerie Casasanto [JCET at GSFC]
Dinosaurs to Milankovitch: A Cautionary Tale	Compton Tucker [GSFC]

On Friday the station was bustling with tourists and locals alike who were eager to listen to Hyperwall talks (see **Photo 12** on page 20) and participate in the activities. In addition to public attendees, approximately 100 students attended the event. See **Table 3** to view the list of Hyperwall stories provided on the second day.

...the station was bustling with tourists and locals alike who were eager to listen to Hyperwall talks...

Table 3. Hyperwall stories from day two of NASA's Earth Day celebration.

Presentation Title	Presenter [Affiliation]
Watching the Earth Breathe Through Satellites and Models	Steven Pawson [GSFC]
Titan and Earth: Climate Cousins	Conor Nixon [GSFC]
Shoot for the Stars No Matter the Odds	Hakeem Oluseyi [NASA HQ]
Sunny with a Chance of Solar Storms	C. Alex Young [GSFC]
Satellites, Ships, Shoes: Observing the Living Ocean from Above	Carlos Del Castillo [GSFC]
GLOBE Observer Mosquito Habitat Mapper App	Kristen Weaver [GSFC]
Exploring the Asteroids	Tom Statler [NASA HQ]
Looking Down on the Earth: Satellites, Science, and Societal Benefit	Michael Freilich [NASA HQ— <i>Director of the ESD</i>]
NASA's Observations, from Fire to Rain, and How We Use Them in Models of the Earth System	Steven Pawson [GSFC]
Walking on the Moon—or Preparing to—With NASA's Lunar Reconnaissance Orbiter	Andrea Jones [GSFC]
ICESat-2 By the Numbers: How Will Satellite Technology Help Us Map the Height of Our Planet?	Brian Campbell [WFC]
Calling All Cloud Gazers: NASA Needs Your Help!	Kristen Weaver [GSFC]
Walking On Other Worlds Without Leaving Earth	Jacob Bleacher [GSFC]
Watching Icebergs Break Away from Antarctica with Landsat	Christopher A. Shuman [JCET at GSFC]
Observations of the Earth at Night	Steve Graham [GSFC]
Exploring the Asteroids	Tom Statler [NASA HQ]
Mapping the Blue Marble	John Bolten [GSFC]
Air Quality from Space: A Tale of 3 Cities	Bryan Duncan [GSFC]
Dinosaurs to Milankovitch: A Cautionary Tale	Compton Tucker [GSFC]

A War Dog Visits Earth Day

Two special guests, their presence organized by Union Station, also stopped by each day at 2:00 PM: Sergeant Micah Jones and his K9 dog *Summer* of the Amtrak Police Department K9 Unit. Summer is a seven-year-old female Labrador Retriever and is considered a *War Dog*. She was deployed with the 1st Battalion, 7th Marines to Camp Leatherneck, Afghanistan in March 2012. Summer, who has been nominated for a Hero Dog Award, made a special on-stage appearance at the Hyperwall to encourage folks to vote for her online (<http://herodogawards.org/dog/summer-jones>).



Sergeant Micah Jones and his K9 dog *Summer* of the Amtrak Police Department K9 Unit. **Photo credit:** NASA



Photo 12. Steve Graham [NASA's Goddard Space Flight Center/ Global Science and Technology Inc.—*Principal Outreach Specialist*] gave a talk titled *The Changing Earth at Night*, where he discussed an image that shows the change in our planet's surface-lighting intensity from 2012 to 2016 (<https://svs.gsfc.nasa.gov/30919>). **Photo credit:** NASA



Photo 13. The *Round Earth Ramblers*, a group of NASA employees, performed American folk and bluegrass music on Friday afternoon. **Photo credit:** NASA



Photo 14. Handwritten thank-you note about NASA's Earth Day celebration at Union Station, written by a five-and-a-half-year-old—possibly a future scientist and concerned citizen. **Photo credit:** NASA

To close the event on Friday, a band of NASA employees called the *Round Earth Ramblers* performed American folk and bluegrass music—see **Photo 13**.

Summary

In the digital age, where even toddlers can manipulate digital devices, face-to-face interactions between the public and NASA's staff still prove to be one of the most effective and inspiring ways to connect with the public, particularly with those who know little about the role NASA plays in Earth science and applications. And while many turned to social media outlets using the NASA hashtag *#NASA4Earth* to join the NASA conversation about Earth Day, others put pen to paper and delivered handwritten thank-you notes to the NASA staff at Union Station—see **Photo 14**. To view more photos from this event, visit <https://www.flickr.com/photos/eosps/albums/with/72157681039942371>. ■

Summary of the 2018 Sun-Climate Symposium

Peter Pilewskie, Laboratory for Atmospheric and Space Physics (LASP) and Department of Atmospheric and Oceanic Sciences, University of Colorado (CU), peter.pilewskie@lasp.colorado.edu

Tom Woods, LASP/CU, tom.woods@lasp.colorado.edu

Vanessa George, LASP/CU, vanessa.george@lasp.colorado.edu

Dong Wu, NASA's Goddard Space Flight Center (GSFC), dong.l.wu@nasa.gov

Odele Coddington, LASP/CU, odele.coddington@lasp.colorado.edu

Introduction

The 2018 Sun-Climate Symposium was held at the University of California, Los Angeles (UCLA) Conference Center in Lake Arrowhead, CA, March 19-23, 2018. The Sun-Climate Research Center—established as a collaboration between NASA's Goddard Space Flight Center (GSFC) and the Laboratory for Atmospheric and Space Physics at the University of Colorado (LASP/CU)—organized this gathering of experts from the solar-terrestrial community and various sun-climate disciplines. The timely theme of the symposium was *The State of the TSI and SSI Climate Records at the Junction of the *SORCE* & *TSIS* Missions*.¹ There were six oral sessions that covered solar and climate observations, models, solar variability, and expectations for the next solar cycle, in addition to two poster sessions spanning these same topics. Over 80 scientists and students from around the world gathered to present their findings and to engage in spirited discussions. Most of the 2018 Sun-Climate Symposium presentations are available online at <http://tinyurl.com/y7jku7zu>.

Meeting Overview

This meeting occurred during an important juncture in the measurement record of solar irradiance. The Solar Radiation and Climate Experiment (SORCE) recently celebrated the 15-year anniversary of its launch, a feat that was celebrated at the symposium—see photo below. SORCE not only ushered in advanced capabilities for measuring total and spectral

¹The acronyms in the title of the symposium are defined in the text that follows.



Celebration cake for SORCE's fifteenth birthday. **Photo credit:** Vanessa George [LASP/CU]



Attendees at the 2018 Sun-Climate Symposium in Lake Arrowhead, CA. **Photo credit:** Vanessa George [LASP/CU]

solar irradiance—accompanied by a large number of science achievements—it has lasted for 10 years beyond its scheduled mission lifetime. In so doing, SORCE has helped preserve the existing 40-year space-based solar-irradiance data record—see **Figure** below.

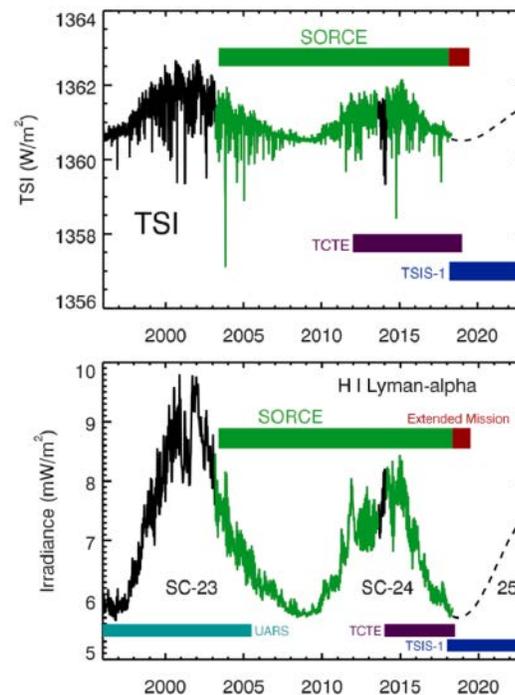


Figure. The solar observations over the Solar Radiation and Climate Experiment (SORCE) mission, shown for total solar irradiance (TSI) [*top*] and the ultraviolet H I Lyman-alpha [*bottom*], include solar cycles 23 and 24, and an extended mission that will include the start of cycle 25. The higher-frequency variations, such as the large dips in the TSI, are caused by the presence of solar active regions rotating with a period of ~27 days. The larger 11-year solar cycle variation is a key forcing function in Earth's atmosphere and climate. **Image credit:** Tom Woods [LASP/CU]



During the meeting the “baton” for total solar irradiance (TSI) and solar spectral irradiance (SSI) monitoring was officially passed from *SORCE* to the Total and Spectral Solar Irradiance Sensor (TSIS-1), though *SORCE* intends to keep on going for at least a year of overlap with TSIS-1 in order to understand potential offsets between the two sets of sensors. **Photo credit:** Peter Pilewskie [LASP/CU]

As *SORCE* winds down, the Total and Spectral Solar Irradiance Sensor-1 (TSIS-1) is just beginning its mission. TSIS-1 was launched to the International Space Station (ISS) on December 15, 2017. The *SORCE*-heritage Total Irradiance Monitor (TIM) and Spectral Irradiance Monitor (SIM) on TSIS-1 have both experienced first light.² Preliminary data from the TIM and SIM instruments on TSIS-1 (referred to henceforth as TSIS TIM and TSIS SIM) were presented at the symposium.

Opening Remarks

Peter Pilewskie and **Tom Woods** [both from LASP/CU—*TSIS-1* and *SORCE* Principal Investigators, respectively] provided opening remarks to put the unique timing of this year’s symposium into perspective. Measurements of solar irradiance from space began four decades ago with the launch of the Nimbus 7 satellite that carried the Earth Radiation Budget (ERB) and Solar Backscatter Ultraviolet (SBUV) sensors.³ Remarkable progress has been made since that time in our ability to monitor ever smaller changes in the sun’s output, integrated over the entire spectrum and in individual wavelength bands, and with increased radiometric accuracy. This has improved our understanding of the sun’s influence on past and present climate, enhanced our ability to predict future climate, and helped us gain insight into the mechanisms by which the Earth system responds to subtle variations in solar irradiance.

During their remarks, Pilewskie and Woods symbolized the linkage between *SORCE* and TSIS using a relay baton that was physically passed from the *SORCE* PI to the TSIS PI: i.e., from one measurement program to the next to continue the four-decades-long solar-irradiance climate data record—see graphic above. We are currently in a one-year overlap period between the *SORCE*, the Total Solar Irradiance Calibration Transfer Experiment (TCTE),⁴ and the TSIS-1 missions.

² To view these images and learn more, see the front cover image and the Editorial of the March–April 2018 issue of *The Earth Observer* [Volume 30, Issue 2, pp.1–3—https://eosps.nasa.gov/sites/default/files/201803/201803_color%20508_0.pdf].

³ To learn more about the Nimbus series and its instruments, see “Nimbus Celebrates 50 Years” in the March–April 2015 issue of *The Earth Observer* [Volume 27, Issue 2, pp. 18–31—https://eosps.nasa.gov/sites/default/files/201503/201503_color_508.pdf].

⁴ TCTE is a payload onboard the U.S. Air Force Space Test Program spacecraft known as STPSat-3, which launched in November 2013.

SORCE still has a firm grasp on the baton that it has ever so gently laid in the hand of TSIS-1. It won’t release that responsibility for several months until after completion of the overlap.

Session 1: The Creation, Significance, and Applications of Accurate Climate Data Records

The symposium kicked off with a session on climate data records (CDRs). The National Research Council (NRC) defines a CDR as “a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change.” Given the nature of this climate-themed symposium it was fitting to have a session that considered: *How are CDRs made, what scientific understanding is gained from them, and what challenges exist for future climate measurement systems and models to produce CDRs?* Presentations during this session answered these and other questions related to CDRs.

Bruce Wielicki [NASA’s Langley Research Center] gave the featured keynote presentation for this session, *Designing the Climate Observing System of the Future*. In it he contrasted the attributes of climate versus weather observations, the distinction being primarily one of accuracy. Maintaining accuracy over decadal time scales is such a challenge that at the present time there is no cohesive global climate-observing system to obtain the 50 or so essential climate variables needed to even adequately describe the state of Earth’s system. Although the costs of establishing such an observing system would require a tripling of what the world currently invests in climate observations, quantitative economic analyses suggest that even the most conservatively estimated returns on that investment will be a factor of several tens or more—considerably more than from other societal investments. Wielicki provided guidelines outlining the need, value, and methods for designing such a future climate observing system, while suggesting that scientists must better articulate to the public the size of the investment required and the tremendous return on that investment that will be realized.

John Bates [John Bates Consulting, Inc.] provided a historical perspective of the NOAA Climate Data Records Program that has now transitioned more than 41 CDRs into initial operating capability. He outlined the evolution from research to initial and then full operational status through the use of a maturity-assessment approach. Bates stressed that an independent CDR maturity assessment should be mandatory and required for any dataset used to help set policy.

A broad range of CDRs was discussed in this session, including the three-decade-long record of sea ice concentration data from passive microwave remote sensing, as were improvements to surface-based aerosol remote sensing from higher-accuracy solar-irradiance spectra. In keeping with the sun-climate theme, other talks covered the incorporation of data from the *SORCE* TIM for constraining Earth's energy budget, the benefit of CDRs, efforts to ensure the continuity of long-term observations of solar activity, and the use of Helioseismic Magnetic Imager (HMI)⁵ data to estimate facular⁶ and network contributions to solar irradiance.

Session 2: The State of the TSI and SSI Climate Records Near the End of the *SORCE* Mission

The focus of this session was on the total solar irradiance (TSI) and solar spectral irradiance (SSI) records since the start of the space era, with emphasis on how measurements of the last decade have been reconciled with and contributed to composite records and their associated time-dependent uncertainties.

Numerous presentations in this session showed TSI measurements from different instruments and missions. Among the highlights were the 21-year record of TSI from *VIRGO* on *SOHO*, Version 2 of *PREMOS* on *PICARD*, and first-light observations from *CLARA* on *NorSat*.⁷ The TIM, first deployed—and still flying—on the *SORCE* mission, now has two companions in orbit, a *SORCE*-era TIM on *TCTE* and the newest version of TIM that is part of *TSIS-1*. Participants got to see the TIM intracomparisons and the intercomparisons of all of these contemporaneous TSI instruments.

SSI measurements from the Sun Monitoring on the External Payload Facility of Columbus-SOLar SPECTral Irradiance Measurements (Solar-SOLSPEC) instrument that flew on the International Space Station for almost nine years have been reanalyzed resulting in a new absolute reference spectrum. These data, like those from the SIM instruments on *SORCE* and *TSIS*, cover well over 90% of the TSI. First-light measurements from the *TSIS* SIM (mentioned previously) were presented during this session. The *TSIS* SIM is off to a good start: its integrated irradiance matches the TIM total irradiance to within the SIM uncertainty of 0.2%.

Other measurements of SSI isolate the ultraviolet regions of the spectrum, where much of the photochemical

⁵ HMI is an instrument that flies on NASA's Solar Dynamics Observatory.

⁶ Faculae are dark regions on the sun's surface.

⁷ *VIRGO* stands for the Variability of Solar Irradiance and Gravity Oscillations, which is an instrument on NASA's Solar and Heliospheric Observatory (*SOHO*); *PREMOS* stands for Precision Monitoring Sensor, which is an instrument that flew on the French *PICARD* mission; and *CLARA* stands for Compact Lightweight Absolute Radiometer, which flies on the recently launched Norwegian *NorSat-1* satellite. (Note: *PICARD* is not an acronym; it was named after seventeenth-century French astronomer Jean Picard.)

reactions in Earth's atmosphere occur. For example, the Ozone Monitoring Instrument (OMI) on *Aura* has a primary mission of measuring atmospheric trace gases, which requires that it acquire SSI data over the 265-500-nm spectral range. The combination of high stability of OMI (in operation since 2004) and a newly revised degradation model has resulted in a high-quality SSI record spanning the entirety of solar cycle 24 (SC24), with the ability to resolve solar variability to better than 0.1%. The OMI SSI dataset was shown during this session. Separating instrument degradation from solar variability remains one of the greatest challenges in developing climate-quality measurement records of solar irradiance. Accordingly, some presentations during this session detailed advanced techniques for deriving instrumental trends and their effects on the data.

Understanding solar influences on the terrestrial environment requires high-fidelity, long-term records of solar irradiance. While improved instrument accuracy and stability and the ability to track instrument degradation is crucial, creating composite records also requires keeping close watch on how overlapping records are merged. Some new methods for creating data composites are not only improving the accuracy of long-term TSI and SSI records, but they now provide time-dependent quantified estimates of uncertainties, an important but often missing attribute that is required for most applications. This session detailed some of these new state-of-the-art approaches for creating TSI and SSI composites. For example, **Thierry Dudok de Wit** [Laboratoire de Physique et Chimie de l'Environnement et de l'Espace, University of Orléans, France] presented a probabilistic and statistically driven approach for creating a TSI composite that relies on weighted contributions from all available datasets at any one time. Participants also learned about improvements in the Spectral and Total Irradiance Reconstruction (*SATIRE*) and Naval Research Laboratory's solar irradiance models (*NRLTSI* and *NRLSSI*) that are used to reconstruct solar irradiance all the way back to the start of sunspot records in the early seventeenth century.

During the session, **Jerry Harder** [LASP/CU] provided some brief remarks commemorating the loss of **Juan Fontenla** [formerly of LASP/CU] in January 2018—see *Remembering Juan Fontenla* on page 24.

Session 3: Next Generation of Solar and Atmospheric Observations

The driving question for this session was: *What new missions, sensors, and implementation strategies will be required for a next-generation observing system to meet the current and future challenges facing climate change studies?* Solar and climate observations are the critical foundations for understanding the current and future of the Earth system, yet the current observing system is inadequate to answer some fundamental questions related to variability over seasonal and longer time scales.

Remembering Juan Fontenla [1948–2018]

Juan Fontenla passed away on January 11, 2018, at his home in Simpsonville, SC. Juan made numerous contributions to the study of the sun and stars during his 37-year career. He is perhaps best known for developing the Solar Radiation Physical Model (SRPM) that he applied to the study of solar spectral irradiance variability for NASA's SORCE mission. As a member of the SORCE science team, Juan was instrumental in the analysis and interpretation of SORCE SIM data. Juan leaves behind his wife and two sons.

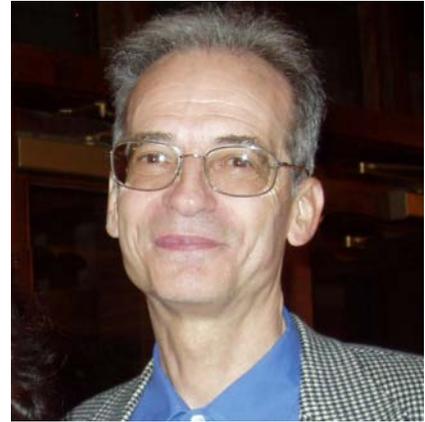


Photo credit: Vanessa George [LASP/CU]

Elizabeth Weatherhead [CU, Cooperative Institute for Research in Environmental Sciences (CIRES)] presented a framework for prioritizing observations that address three different objectives: trend detection, short-term process studies, and seasonal forecasting. She stressed that prioritizing the needed observations should not be limited by current technologies, but they should be rigorously and independently evaluated to assure that the observing system is sufficient for the proposed goals.

There is reason to be optimistic that next-generation missions will improve our climate-observing capabilities. For example, the NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, scheduled for launch in 2022, will extend key heritage ocean color, cloud, and aerosol data records, while providing new insight into oceanographic and atmospheric responses to Earth's changing climate. PACE will fly a spectroradiometer and two polarimeters that will revolutionize studies of global biogeochemistry, carbon cycles, and aerosols in the ocean-atmosphere system.⁸

New small and highly capable instruments are in the planning stages for future solar- and Earth-viewing observations of the global energy budget. The Compact Spectral Irradiance Monitor (CSIM) and the Compact Total Irradiance Monitor (CTIM) employ vertically aligned carbon nanotube (VACNT) bolometers to meet climate-quality requirements of solar irradiance but with reduced mass, volume, and power consumption compared to their predecessors—the TIM and SIM instruments currently flying on SORCE and TSIS-1. CSIM is scheduled for launch in late 2018, while the CTIM will be built and environmentally qualified in 2018-2019 in preparation for a future flight opportunity.

⁸ To learn more about PACE, see “NASA sets the PACE for Advanced Studies of Earth's Changing Climate” in the July–August 2015 issue of *The Earth Observer*, [Volume 27, Issue 4, pp. 4-12—https://pace.gsfc.nasa.gov/docs/earth_observer_jul_aug_2015.pdf].

Another experiment is the Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) 3U CubeSat, which was launched in November 2016 and is still operating. RAVEN is a pathfinder for a future constellation implementation to measure the Earth's radiative energy imbalance. The Swiss Physical Meteorological Observatory (PMOD)/World Radiation Center (WRC) in Davos has developed the highly versatile Davos Digital Absolute Radiometer (DARA) to measure TSI on diverse missions like the ship-tracking microsatellite on the Norwegian NorSat-1 mission, the Chinese FengYun-3 (FY-3E) meteorological observatory, and the European Space Agency's PROBA-3⁹ solar occultation mission. Modified versions of the DARA instrument have been proposed to measure Earth's radiation imbalance in future missions, similar to the RAVEN concept.

After Session 3 there was an optional excursion to Big Bear Solar Observatory to see the world's highest-resolution solar telescope—see *A Trip to Big Bear Solar Observatory* on page 25.

Session 4: Impacts of Solar Variability on the Terrestrial Environment during Solar Cycle 24

This session addressed the following questions relevant to solar variability's impacts on Earth's environment:

- *With SC24 being one of the weakest during the past 90 years, can we reliably discern the terrestrial signatures of the current solar inactivity—at the surface, in the stratosphere, and in space weather?*
- *It has been established that the upper-atmosphere density has had a long-term decrease from cooling above 300 km (~186 mi) by greenhouse gases and due to the reduced solar activity in SC24. Are there*

⁹ PROBA-3 is the third in the European Space Agency's series of PROBA low-cost satellites that are being used to validate new technologies for spacecraft, while also carrying a scientific payload.

similar indications in the lower atmosphere for warming due to greenhouse gases and other changes due to reduced solar activity?

- *What does understanding of the present (in the context of the past) infer for the future variability of Earth's environment?*

Lesley Gray [University of Oxford] delivered a keynote address centered on these themes. She highlighted the 11-year variability in weather patterns over Europe that is driven by the North Atlantic Oscillation (NAO). As is often the case in correlating weather and climate signals with the solar cycle, the signal appears to be present in some periods but not others, suggesting that

it may be a random artifact. Using data going back to 1660, Gray showed evidence of an 11-year signal in weather patterns but with a response that varied in strength and phase with an 11-year solar-forcing cycle. She proposed that a coupled atmosphere–ocean mechanism could explain a lag in response of three to four years. The resultant observed signal would depend on the strength of this mechanism in addition to solar ultraviolet forcing of stratospheric temperatures and wind and subsequent response at the surface.

The session was as diverse as its description suggested. Solar-cycle induced variability in middle atmosphere carbon monoxide and nitrogen dioxide levels, cloud cover over the poles, Arctic ozone, El Niño and La Niña

A Trip to Big Bear Solar Observatory

On the afternoon of the third day of the symposium, attendees had the opportunity to visit Big Bear Solar Observatory (BBSO). BBSO is operated by the New Jersey Institute of Technology (NJIT), with funding from the National Science Foundation, NASA, the U.S. Air Force, the Korean National Science Foundation, and other government and private sources. It is home to the world's highest-resolution solar telescope, recently renamed the Goode Solar Telescope (GST) after former director Phil Goode [NJIT] who was instrumental in its design, construction, and realization. Current Director **Wenda Cao** [NJIT] gave a short presentation at the symposium on the history, achievements, and capabilities of BBSO.

The 1.6-m (~5-ft) clear-aperture, off-axis GST was the first facility-class* solar telescope built in the U.S. in a generation. Benefitting from the long periods of excellent seeing conditions at Big Bear Lake, the GST can produce simultaneous images of massive explosions such as solar flares and coronal mass ejections that occur at approximately the same time across structures as large as a 20,000 mile-wide sunspot in the sun's photosphere. Since beginning regular operation in 2010, it has provided the community with open access to observations of the solar photosphere, chromosphere, and up to the base of the solar corona with unprecedented resolution, targeting the fundamental nature of solar activity and the origin of space weather. There are two other facilities at BBSO, housing an "earthshine" telescope and a Global Oscillation Network Group (GONG)** telescope.



Some of the Sun–Climate Symposium participants enjoyed an afternoon trip to nearby Big Bear Solar Observatory to see the world's highest-resolution solar telescope. **Photo credit:** Tom Woods [LASP/CU]

*A *facility-class instrument* is one designed as a standard instrument for community use. This distinguishes it from a *principal investigator (PI) instrument*, which is custom-designed for use by an individual investigator. Researchers can simply specify what measurements they want from a facility instrument, and the on-site operator can acquire the data and send it to the remote investigator.

**GONG is a community-based program to conduct a detailed study of solar internal structure and dynamics using helioseismology. Learn more at <https://gong.nso.edu>.

patterns, and the East Asian Monsoon were addressed. New results from Coupled Model Intercomparison Project Phase 5 (CMIP-5) provided evidence that the response of climate models to solar variability has improved, with subsequent impacts on the attribution of observed recent surface temperature variability. There was also discussion about longer-term solar variability—consistent with the Centennial Gleissberg Cycle (CGC)¹⁰—which has a climate response that is distinctly different from other sources of climate forcing.

Session 5: Stellar Variability and Connections to the Sun

Presentations given during this session addressed the following specific questions on stellar variability as it relates to the sun.

- *How typical is the cyclic activity of our sun relative to sun-like stars?*
- *What have we learned from NASA's Kepler Mission¹¹ and ground-based synoptic programs about the ranges of total and spectral irradiance variability?*
- *What progress have we made in understanding what controls the amplitude and length of cyclic activity in a sun-like star?*

Jeffrey Hall [Lowell Observatory] delivered the keynote presentation on the variability of sun-like stars. He reported that we now have a reasonably comprehensive picture of solar variability in the stellar context. Significant progress has been made in cross-calibration between datasets from the Lowell Observatory Solar-Stellar Spectrograph project and Mount Wilson Observatory HK Project. He provided evidence of what could be the first confirmation of a sun-like star in a Maunder Minimum transition.

Other presentations during this session revealed several of the advances made in understanding our sun through the behavior of sun-like stars. For example, the sun's rotation rate and magnetic field are currently in a transitional phase typical of middle-aged stars—the solar cycle is currently growing longer on stellar evolutionary time scales that will end with the shutdown of the global dynamo sometime in the next 0.8–2.4 Gyr.

This leads to the question: *How typical is the sun as a variable star?* A longstanding puzzle that solar brightness variability over the 11-year activity cycle is anomalously low compared to that of sun-like stars with

¹⁰ The CGC is a 90–100 year cycle in the sunspot number, geomagnetic activity, occurrence of midlatitude auroras, and large fluence Solar Energetic Particle events.

¹¹ This mission is specifically designed to survey our region of the Milky Way galaxy to discover hundreds of Earth-size and smaller planets in or near the habitable zone and determine the fraction of the hundreds of billions of stars in our galaxy that might have such planets.

similar levels of magnetic activity was explained on the basis of small differences of stellar metallicity. Another way to map what is observed from stellar brightness variability onto solar variability is to imagine how the sun's brightness would vary if observed from Kepler, that is, out of the ecliptic. This helps determine how our concepts of solar brightness variability have to be altered to reproduce the distribution of observed variability in Sun-like stars.

Exoplanets were another topic of discussion in this session. Magnetic activity and flares from exoplanet type-M dwarf host stars were reviewed because they are often targets for habitable-zone planet searches. There is still much that is unknown about type-M dwarf flare spectra in the near-ultraviolet between 200–350 nm, an important wavelength range for planetary surface biology and ozone chemistry in habitable-zone planets. Climate and habitability of Earth-like exoplanets was also the focus of another presentation. Since we now have evidence from Kepler that extrasolar planets are quite common, the next steps are to confirm the existence of habitable, or even inhabited extrasolar planets. Future observations from the James Webb Space Telescope and the next generation of 30-m ground-based telescopes will begin observing these worlds.

Session 6: What Are the Expectations for the Next Solar Minimum and Solar Cycle 25?

The presentations in this session addressed the following questions related to predicting how the next solar cycle will behave:

- *Are spectral and total solar irradiance levels lower now than during past minima? How much will they change during SC25?*
- *Are we entering a new prolonged period of anomalously low activity such as the Dalton Minimum in the early 1800s?*
- *Can we identify anomalous behavior in the solar dynamo and surface magnetic flux transport as we enter this next cycle minimum? Do they provide insight into the activity level of the next cycle?*

Scott McIntosh [National Center for Atmospheric Research/High Altitude Observatory] gave the keynote presentation for this session, during which he provided a fascinating picture of solar variability and its predictability based on the 22-year solar magnetic cycle. Tracking the evolution of small-scale magnetic features in the solar corona can explain the behavior of present, current—and potentially future—sunspot cycles. Contemporary observations of the solar corona reveal long-lived patterns that mark the 22-year solar magnetic activity cycle. The modulation of these patterns can explain the landmarks of the sunspot cycle that occur over about half of the magnetic cycle span.

These features suggest that solar minimum for SC24 is almost at hand, that SC25's sunspots will begin to appear in late 2019 to early 2020, and that SC25 will be weaker than SC24. It should be noted that **Leif Svalgaard** [Stanford University] posited the opposite—i.e., that SC25 would be larger than SC24. This prediction is based on the magnitude of the sun's polar fields as derived from the solar axial dipole moment.

Others in this session discussed the underlying mechanisms of solar variability. Several *dynamo theories*—which are the basis for many prediction schemes—were reviewed and critically examined over solar-cycle-to-much-longer, climate-relevant time scales. *Helioseismology*, an important tool for detecting plasma motion deep inside the sun, has revealed that the internal flows are generally more complex than is assumed by dynamo theories. Finally, there was discussion of morphology and evolution of faculae and comparisons of galactic cosmic-ray intensities with estimates from cosmogenic isotopes.

Conclusion

NASA's Earth Science missions, including the SORCE and TSIS-1 missions, are critical for advancing our understanding of the complexity of Earth's systems and their connection to the encompassing solar environment; new climate missions are required to continue

these valuable climate records. The 2018 Sun-Climate Symposium emphasized the connections between solar variability and Earth's climate at an important juncture in the measurement record during overlap of the SORCE and TSIS-1 missions. Moreover, we are also approaching a minimum in the sun's activity cycle; how the sun will vary over the next cycle and the Earth system response are intense areas of study. The Sun-Climate Symposium addressed these issues in the context of present-day climate change and anthropogenic and natural drivers. The multidisciplinary nature of the meeting brought together specialists in measuring and modeling the sun's output and Earth's radiation budget, climate and atmospheric modelers who interpret those and other forcings and quantify Earth's changing environment, solar physicists who study how the sun varies, and other specialists developing new instruments and missions to address some of the questions that were addressed in the meeting. The meeting participants look forward to the next symposium, when updates on some of the most vexing issues in Sun-Earth connections will be discussed, as new questions are sure to arise.

To stay up to date on the latest TSIS and SORCE news and meeting announcements, read the TSIS/SORCE newsletter at <http://lasp.colorado.edu/home/sorce/news-events/newsletter>. ■

KUDOS: Claire Parkinson Elected 2018 Academy Fellow

Claire Parkinson [NASA's Goddard Space Flight Center—*Aqua Project Scientist*] has been elected a Fellow of the American Academy of Arts and Sciences—one of 177 elected in 2018.

As one of the country's oldest learned societies and independent policy research centers, the Academy convenes leaders from the academic, business, and government sectors to respond to the challenges facing the nation and the world. Others elected this year include, most prominently, former President Barack Obama and actor Tom Hanks. The complete list of Academy Fellows (177) and International Honorary Members (36) elected in 2018 can be viewed at <https://www.amacad.org/content/members/newFellows.aspx?s=c>.

The Earth Observer congratulates Parkinson on this prestigious honor!



2018 Arctic-Boreal Vulnerability Experiment (ABOVE) Open Science Team Meeting Summary

Scott Goetz, Northern Arizona University, scott.goetz@nau.edu

Chip Miller, NASA/Jet Propulsion Laboratory, charles.e.miller@jpl.nasa.gov

Peter Griffith, NASA's Goddard Space Flight Center/SSAI, peter.c.griffith@nasa.gov

Dan Hodkinson, NASA's Goddard Space Flight Center/SSAI, daniel.j.hodkinson@nasa.gov

Libby Larson, NASA's Goddard Space Flight Center/SSAI, libby.larson@nasa.gov

Elizabeth Hoy, NASA's Goddard Space Flight Center/GST, elizabeth.hoy@nasa.gov

Introduction

The Arctic-Boreal Vulnerability Experiment (ABOVE), organized under the auspices of NASA's Terrestrial Ecology Program, is an approximately 10-year campaign to study environmental and climatic changes and their implications for social and ecological systems in Alaska and north-west Canada. Currently in its third year of implementation, ABOVE is comprised of 83 research projects¹ funded by NASA and other partner agencies such as the U.S. Department of Energy, the National Science Foundation, Natural Resources Canada, POLAR Knowledge Canada, and the Natural Sciences and Engineering Research Council of Canada, among others. For more information on ABOVE, visit <https://above.nasa.gov>.²

ABOVE held its fourth annual Science Team Meeting in Seattle, WA, January 23 - 26, 2018. This was the first time that the Science Team Meeting allowed for broad participation from all science team members; thus, over 150 attendees from NASA, other U.S. federal, state, and Canadian agencies, and U.S. and Canadian universities attended. Participants from NASA Headquarters (HQ)—including **Hank Margolis** [*ABOVE Program Manager*], **Eric Kasischke** [*ABOVE Program Scientist*], and **Ken Jucks** [*Program Manager for the Upper Atmosphere Research Program*—were able to attend by the second day of the meeting.³ Invitational travel

¹ View project profiles at https://above.nasa.gov/profiles/_projectProfiles.html.

² Also reference, "The Arctic—Boreal Variability Experiment (ABOVE) Science Team Summary," in the May–June 2017 issue of *The Earth Observer* [Volume 29, Issue 3, pp. 17–20—https://eosps.nasa.gov/sites/default/files/eo_pdfs/May%20June%202017%20color%20508.pdf].

³ The brief U.S. Federal Government shutdown prevented them from being present the first day of the meeting.

assistance helped 20 graduate students and 17 postdoctoral researchers (all from the U.S.) attend the meeting.

Meeting Summary

Scott Goetz [Northern Arizona University (NAU)—*ABOVE Science Lead*] and **Peter Griffith** [NASA's Goddard Space Flight Center (GSFC)—*Director of the Carbon Cycle & Ecosystems Office*] convened the meeting by highlighting the successes and challenges of the previous year, followed by an overview presentation by **Charles "Chip" Miller** [NASA/Jet Propulsion Laboratory (JPL)—*ABOVE Deputy Science Lead*] on the completion of the first ABOVE Airborne Campaign—see **Figure**. Airborne science team leads gave presentations on individual airborne instrument activities, including L- and P-band synthetic aperture radar (SAR), the Land, Vegetation, and Ice Sensor (LVIS), the next-generation, narrow-band Airborne Visual-Infrared Imaging Spectrometer (AVIRIS-NG), the Canopy Fluorescence Imaging Spectrometer (CFIS), and the Air Surface Water and Ocean Topography radar (AirSWOT; a K_a band system). The presentations highlighted the importance of the ABOVE airborne and field (ground-based) activities, including discussions on how to advance the scaling of field measurements to satellites via airborne data acquisitions.

After these opening presentations, participants immersed themselves in the latest in ABOVE science via a series of invited plenary talks, partner presentations, poster sessions, and breakout discussions, the highlights of which are summarized below.

All presentations, including breakout session reports, can be downloaded from https://above.nasa.gov/meeting-jan2018/agenda_final.html.



Photo of the ABOVE Science Team, with staff from NASA's Goddard Space Flight Center, Carbon Cycle & Ecosystems Office. **Photo credit:** Sarah Sackett

Plenary Sessions

The plenary sessions highlighted some key science topics that are relevant to ABoVE. They also set up the breakout session discussions (described later) and ABoVE research generally, in a broader context.

Ted Schuur [Northern Arizona University] described recent research syntheses, relying in part on ABoVE data and resulting publications, that better characterize permafrost carbon storage in frozen soils from Ice Age to present conditions, including accounting for transformations of carbon in lake sediments during cycles of freezing and thawing.

David Butman [University of Washington] and **Robert Striegl** [U.S. Geological Survey] highlighted the variability of movement patterns of permafrost carbon due to differences in soil type and hydrologic conditions.

Ralph Keeling [Scripps Institute of Oceanography] demonstrated that the general global trend toward having a longer growing season alone does not account for increases in the amplitude of the carbon dioxide (CO₂) cycle over recent decades, especially at high latitudes. This finding emphasizes the need for future analyses of the interacting roles of CO₂ fertilization, warming, drought, and fire disturbance.

Michelle Mack [Northern Arizona University] reported that despite the increased severity of burning in boreal ecosystems, mineral soil carbon remaining in previously burned areas is not being combusted.

Joshua Fisher [JPL] presented information on ecosystem model improvements in estimating carbon fluxes, and highlighted plans for the next phase of ABoVE modeling, which includes data-to-model translation, operational benchmarking, and structured model development.

Partner Presentations

Partner presentations complemented the plenary talks and breakout session discussions by providing overviews of potential synergies with large research programs.

Shawn Serbin [Brookhaven National Laboratory] described the recent work of the U.S. Department of Energy's Next Generation Ecosystem Experiment – Arctic (NGEE-Arctic) field campaign in Alaska, demonstrating how data from the ABoVE airborne campaign allow scaling-up field measurements of biomass, plant structure, and type to regional scales.

Adam Houbin [POLAR Knowledge Canada] reported on recent activities of their Canadian-funded ABoVE projects, especially those focused on ecosystem research being conducted in Nunavut, Canada.

Merritt Turetsky [University of Guelph] introduced the newly funded Northern Water Futures, a project of Global Water Futures (<https://gwf.usask.ca>), and

suggested potential synergies with existing ABoVE projects, e.g., comparing Northern Water Futures' data from peatlands in the Northwest Territories with similar Alaskan ecosystems that are part of ABoVE projects.

Jason Edwards [Natural Resources Canada] reported on the activities of the Canadian Forest Service, including their work on updating their forest inventory by integrating remote sensing and field data.

Andrew Applejohn [Government of the Northwest Territories (GNWT)] described the research priorities of the Government of the Northwest Territories, highlighting the overlap of interests with ABoVE regarding permafrost, carbon cycling, wildfires, vegetation, and wildlife habitat. Enhanced understanding of these topics is especially important to GNWT land managers and other decision makers. ABoVE products contribute significantly to the research and management capacity of the GNWT.

Special Presentation from an ABoVE Veteran

A highlight of the meeting was the presentation by **Eric Kasischke** [NASA HQ/University of Maryland], titled *The Boreal-Arctic Research Continuum – Perspectives from an Old-Timer*. Kasischke played a foundational role in the development of ABoVE as a concept for a Terrestrial Ecology Field Campaign. Beginning as an author on the initial scoping study in 2009 and ending as ABoVE Program Scientist at NASA Headquarters, his work has been vital to the success of ABoVE. He emphasized the fact that understanding the changes that are happening in this region requires long-term, coordinated, transdisciplinary monitoring and research—then used his own career as an example of such an effort. In his specific case, his 25 years of research has substantially increased our understanding of boreal forest fire ecology. He then prompted the audience to think long-term, and consider how the monitoring and research efforts initiated during ABoVE could continue after the campaign is over, and how they might contribute to national and international programs focusing on the broader High Northern Latitude region. Kasischke will retire in May 2018, and the community appreciated the opportunity to hear his retrospective presentation.

Applied Sessions

There were also after-lunch applied sessions focused on relevant upcoming satellite missions (e.g., ICESat-2 and NISAR, both of which will provide data that can be used to evaluate vegetation structure and permafrost thaw);⁴ a composited, high-resolution, digital elevation model (DEM) for the ABoVE domain; modeling with

⁴ ICESat-2 stands for Ice, Cloud, and land Elevation Satellite-2, planned for launch later this year. NISAR is a compound acronym that stands for NASA–Indian Space Research Organization (ISRO) Synthetic Aperture Radar, a joint NASA–ISRO venture, planned for launch in 2022.

an atmospheric transport model (WRF-STILT);⁵ new capabilities on the ABoVE Science Cloud; and data-management sessions to enhance integration of data for synthesis activities. These sessions also emphasized the importance of good data management practices, as reflected in the 63 data products already published at the Oak Ridge National Laboratory Distributed Active Archive Center by ABoVE researchers.

Breakout Sessions

A key aspect of the Science Team Meeting was the opportunity for the ABoVE interdisciplinary working groups to meet both individually and across topic areas to advance ongoing synthesis activities, identify knowledge gaps, and discuss potential new synthesis activities. Each day allowed for ample time for such discussions during the breakout sessions, with groups reporting back to the larger group the next day. For a list of the primary science ABoVE working group leads, see the **Table**. For a full list of all working groups, visit https://above.nasa.gov/cgi-bin/above_wg.pl.

Table. ABoVE Science Team interdisciplinary working groups and chairpersons.

Working Group	Chair(s) [Affiliation(s)]
Hydrology and Permafrost	John Kimball [University of Montana]
Vegetation Dynamics	Howard Epstein [University of Virginia] and Mike Goulden [University of California, Irvine]
Fire Disturbance	Michelle Mack [Northern Arizona University]
Carbon Dynamics	Abhishek Chatterjee [GSFC], Roisin Commanc [Columbia University], and Sue Natali [Woods Hole Research Center]
Wildlife and Ecosystem Services	Natalie Boelman [Lamont-Doherty Earth Observatory/Columbia University]
Modeling Framework and Comparisons	Joshua Fisher [JPL]

Conclusion

Overall, it was clear to the attendees that ABoVE continues to be an innovative and productive activity. The plenary sessions provided an opportunity for the individual science team members to learn about the activities of the 2017 ABoVE Airborne Campaign, the scientific, cross-project syntheses that are beginning to emerge from ABoVE research, and the ongoing activities of our state, national, and international partners. The applied sessions allowed for more in-depth exploration of technical

⁵ WRF-STILT stands for Weather Research Forecasting – Stochastic Time-Inverted Lagrangian Transport Model.



Figure. As-flown flight lines from the 2017 ABoVE Airborne campaign conducted surveys across more than 4 million km² (more than 1,544,000 mi²) of Arctic-boreal North America, sampling critical ecosystems, gradients, and bioclimatic zones. To learn more, visit <https://above.nasa.gov/airborne/flightlines.html>. **Figure credit:** Elizabeth Hoy

issues, approaches, and tools of ABoVE researchers. The breakout sessions enabled thematic teams to discuss current and ongoing collaborations, with additional time provided from cross-thematic discussions. And finally, the community enjoyed the historic perspective of Eric Kasischke’s farewell presentation.

In part due to the “pre-ABoVE” projects initially funded in 2013–2014 (see previously mentioned website with project details), there are already 81 publications by 20 of the 62 NASA-funded projects. Many of these publications appear in top-tier journals including *Nature*, *Science*, and *Proceedings of the National Academy of Sciences of the United States of America* (PNAS). In addition, ABoVE-affiliated and -partner projects (i.e., those not funded by NASA) reported an additional 64 publications—mostly from research conducted in the Next-Generation Ecosystem Experiments-Arctic (NGEE-Arctic) project. ABoVE also has a dedicated collection of papers forthcoming in the journal *Environmental Research Letters*. This special collection will be open throughout the duration of ABoVE, addressing the influence and impact of environmental changes, taking place across the high northern latitudes and their influence on Arctic and boreal ecosystems.⁶

The next ABoVE Science Team Meeting will be held April 1–4, 2019, at the Scripps Seaside Forum in La Jolla, CA. Keep an eye on the ABoVE Meetings and Events page at <https://above.nasa.gov/meetings.html?> for future information. ■

⁶ More information on the collection is available at <http://iopscience.iop.org/journal/1748-9326/page/ABoVE>.

NASA Mapping Hurricane Damage to Everglades, Puerto Rico Forests

Kate Ramsayer, NASA's Goddard Space Flight Center, kate.d.ramsayer@nasa.gov

EDITOR'S NOTE: This article is taken from *nasa.gov*. While our intent is to reprint it with its original form largely intact, in this case, we did update the last paragraph to contain up-to-date information.

Last spring, NASA researchers flew over the Florida Everglades and Puerto Rico to measure how mangroves and rainforests grow and evolve over time. Five months later, hurricanes Irma and Maria tore through those study areas—creating a unique opportunity to investigate the devastating effects of massive storms on these ecosystems, as well as their gradual recovery—see **Figure 1**.

Flying the same paths over the Everglades three months after Hurricane Irma, the scientists' preliminary findings reveal that 60% of the mangrove forests analyzed were heavily or severely damaged. In April 2018, the team returned to Puerto Rico to conduct an airborne survey of the rainforest there—quantifying the damage and possibly identifying sites vulnerable to landslides.

The view of southeastern Florida, less than three months after Hurricane Irma hit, revealed swaths of leafless trees and broken branches, even uprooted mangrove trees.

“It’s staggering how much was lost. The question is, which areas will regrow and which areas won’t,” said **Lola Fatoyinbo** [NASA’s Goddard Space Flight Center (GSFC)—*Research Physical Scientist*]. “This is an opportunity—with all these data, we can really make a difference in understanding how hurricanes impact Florida’s mangrove ecosystems.”

The South Florida project started with a question about how freshwater ecosystems, such as sawgrass marshes of the



Figure 1. Damage to the Florida Everglades is seen from the air, as Goddard’s Lidar, Hyperspectral and Thermal Imager (G-LiHT) team captured images of the same mangrove ecosystem of Ten Thousand Islands before Hurricane Irma, on March 28, 2017 (top), and after the hurricane, on December 1, 2017 (bottom). **Credit:** NASA

Everglades, are transitioning to saltwater ecosystems. This change, which can result from rising sea level and coastal erosion, can impact the local soil microbes, vegetation and even the aquifers Miami draws on for its drinking water.

The scientists have been using data from the Landsat satellites to measure the extent of hurricane damage to the forests over the last 30 years. The Landsat imagery not only provides information about the extent of the damage, but also the time, it takes the forest to recover. At the same time the satellite imagery can also identify areas where vulnerable forests were replaced with open water.

“We want to know how fast this transition is happening. Combining the spatial changes measured by satellite with the structural information we measure from the air we can estimate where the key habitats are that are most vulnerable to hurricanes and saltwater intrusion,” said **David Lagomasino** [GSFC—*Postdoctoral Scientist*].

A team of scientists worked with local land managers, including the Everglades National Park and Florida Fish and Wildlife, to plan and execute data-collecting flights in April 2017. They took measurements using a scientific instrument called Goddard’s Lidar, Hyperspectral and Thermal Imager (G-LiHT), which collects multiple measurements simultaneously, including the heights of the vegetation from a lidar instrument, and high-resolution photographs.¹

“We had this amazing dataset—then the hurricane went through,” Lagomasino said. Hurricane Irma, with winds upwards of 140 mi/hr (225 km/hr), swept through the Everglades National Park on September 10, 2017. “Hurricanes are a natural part of the ecosystem, and we know that after hurricanes the ecosystem does return for the most part. But not a hundred percent.” Areas without surviving or regrowing mangrove trees may put neighboring ecosystems at risk of additional impacts from storm surges and saltwater intrusion.

After the team reflew the same paths across 500 mi² (1300 km²) of wetlands, a preliminary analysis of the two sets of flights found that gaps in the canopy from snapped branches and uprooted trees covered 40% of the area. In areas hit the hardest, the height measurements from G-LiHT showed that the average height of

the forest canopy was shortened by 3 to 5 ft (1 to 1.5 m) due to fallen branches and trees.

The researchers also joined scientists from local agencies and organizations to measure the hurricane impact from the ground. Hiking into the wetlands, they used laser scanners to take three-dimensional images of the trees, branches and even leaves that make up the forest structure—see **Figure 2**.



Figure 2. Researchers used laser and stereoscopic instruments to collect three-dimensional information of hurricane-damaged mangrove forests from the ground as well as from planes. Here, a ground-based lidar captures researchers within a mangrove forest in Ten Thousand Islands in southwest Florida, displaying much finer detail on the ground than available from the air. **Credit:** NASA

“The number of downed trees, just completely splintered in some cases, was impressive to see,” said Lagomasino.

The team now plans to compare datasets from before and after the hurricane to see if the areas that were under stress before the storm—whether from saltwater encroachment, nearby developments, or other reasons—correspond with the areas that don’t recover as quickly, or don’t recover at all. Lagomasino would also like to look for other damage patterns and estimate tree mortality. Collectively, the G-LiHT data will help provide a better understanding of the vulnerability of Florida’s coastal ecosystems to storms.

“There’s so much data, and we’re trying to see now what could give us important information about the landscape before we head into the next hurricane season,” Lagomasino said. “There’s a lot to do.”

From April 17 to May 2, 2018, G-LiHT flights crisscrossed the island of Puerto Rico, which was hit by both Hurricane Irma and the Category 4 Hurricane Maria. Altogether the flights totaled 3023 km (~1878 mi), with more than 12 billion laser shots fired over 81,430 ha. This means that the store of post-hurricane data—all free and available to the public—continues to grow. ■

¹To learn more about G-LiHT, visit <https://gliht.gsfc.nasa.gov>.

NASA's New Space 'Botanist' Arrives at Launch Site

Esprit Smith, NASA/Jet Propulsion Laboratory, esprit.smith@jpl.nasa.gov

Alan Buis, NASA/Jet Propulsion Laboratory, alan.d.buis@jpl.nasa.gov

EDITOR'S NOTE: This article is taken from *nasa.gov*. While it has been modified slightly to match the style used in *The Earth Observer*, the intent is to reprint it with its original form largely intact.

A new instrument that will provide a unique, space-based measurement of how plants respond to changes in water availability has arrived at NASA's Kennedy Space Center in Florida to begin final preparations for launch to the International Space Station this summer aboard a cargo resupply mission—see photo.

NASA's ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) left NASA's Jet Propulsion Laboratory, on April 6, 2018, by ground transport and arrived at NASA's Kennedy Space Center on April 9, 2018.

A few days after it reaches the space station, ECOSTRESS will be robotically installed on the exterior of the station's Japanese Experiment Module Exposed Facility Unit (JEM-EF)—see **Figure**.

ECOSTRESS will give us new insights into plant health by quantifying the temperature of plants from space as never before, measuring regions as small as 230 ft (70 m) on a side, or about the size of a small farm. It will do this by estimating how much water plants are releasing to cool themselves (i.e., *evapotranspiration*—the equivalent of sweating in humans). This will tell us how much water different plants use and need, and how they react to environmental stresses caused by water shortages. ECOSTRESS will estimate how much water moves through and out of plants by tracking how the temperatures of plants change. The data from its minimum one-year mission will be used by ecologists, hydrologists, agriculturalists, meteorologists, and other scientists.¹

“Most satellite measurements of plant surface temperature are made at a particular time of

¹To learn more about ECOSTRESS, visit <https://ecostress.jpl.nasa.gov>.

day, often in the mid-morning, when plants are not stressed,” said **Simon Hook** [NASA/Jet Propulsion Laboratory (JPL)—*ECOSTRESS Principal Investigator*]. “ECOSTRESS takes advantage of the space station's orbit to obtain measurements at different times of day, allowing us to see how plants respond to water stress throughout the day.”

Until now, scientists addressing this question globally have had to estimate how that same-time-of-day snapshot varies over the course of a day. ECOSTRESS promises to eliminate much of this guesswork.



NASA's ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) is inspected after arrival at NASA's Kennedy Space Center. **Photo credit:** NASA

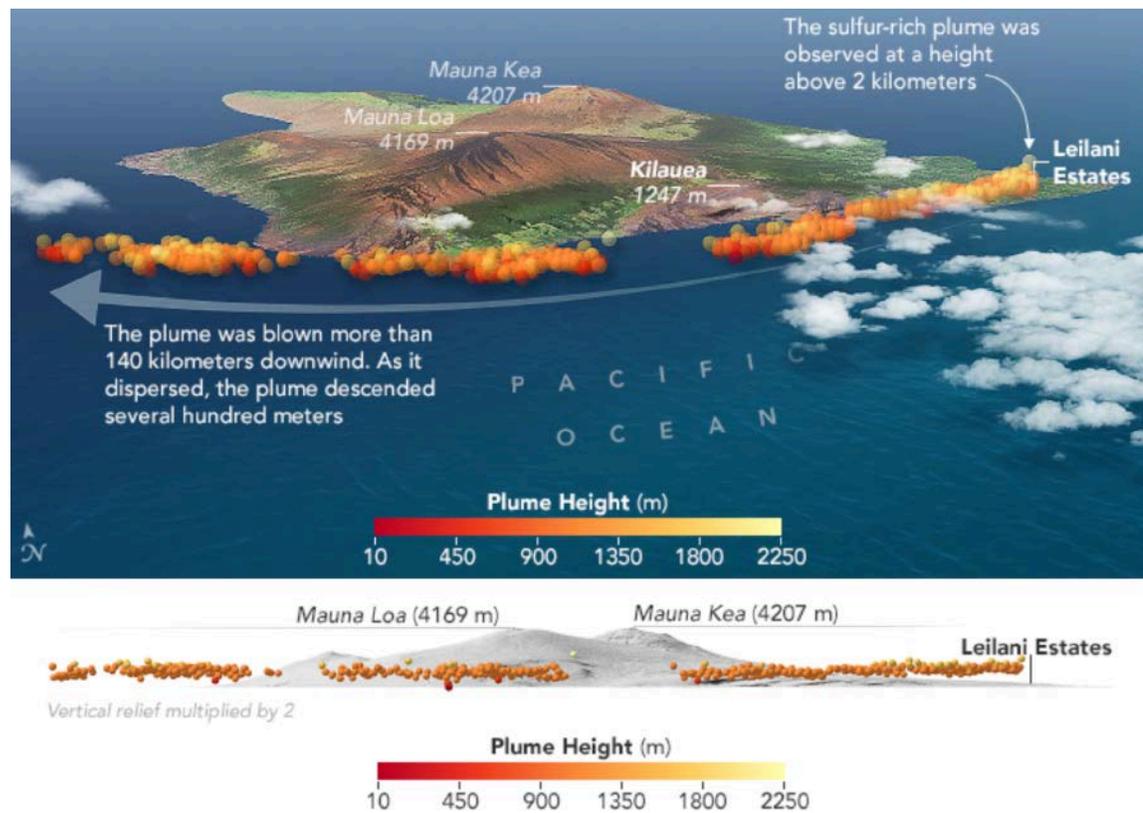


Figure. This drawing shows the configuration of ECOSTRESS once it is installed on International Space Station's Japanese Experiment Module - External Facility (JEM-EF) site 10. The investigation will take advantage of the space station's orbit to measure plant surface temperatures at different times of day, allowing scientists to see how plants respond to water stress throughout the day. **Credit:** NASA

ECOSTRESS is expected to provide key insights into how plants link Earth's global carbon and water cycles. ECOSTRESS data will be used in conjunction with other satellite and ground measurements, such as those from NASA's Orbiting Carbon Observatory-2 (OCO-2) satellite. By doing this, scientists hope to understand more clearly the total amount of carbon dioxide plants remove from the atmosphere during a typical day. In addition, they hope to better identify which areas on the planet require more or less water for the amount of carbon dioxide they take up.

In practical terms, the year of data gleaned from ECOSTRESS will be useful for agricultural water managers. These data should improve our understanding of how certain regions are affected by drought and help agricultural and water management communities better manage water use for agriculture. The high ground spatial resolution of ECOSTRESS data will be useful for research on the effects of drought on agriculture at the field-scale. ■

From NASA's Earth Observatory



Though Hawaii's Kilauea has been erupting continuously since 1983, the eruption took a dangerous turn on May 3, 2018, when several new fissure eruptions emerged in a residential neighborhood (Leilani Estates). The images above show observations of the height of the plume on May 6, 2018, from the Multi-angle Imaging Spectroradiometer (MISR) sensor on NASA's Terra satellite. The top map represents the sulfur-rich plume represented in three dimensions as it moved downwind of the active fissures. The second image depicts the same data as a cross section, with the height of Mauna Loa and Mauna Kea for comparison. The MISR data indicate that, on May 6, the top of the plume was injected to roughly 1.5 km (1 mi) above sea level, but then descended several hundred meters as it moved 140 km (90 mi) downwind. Winds blew the plume southwest along the coast, but over the ocean, away from where people live. Low plumes like this are closely watched because they can pose health hazards if harmful gases and particles move toward population centers. **Credit:** NASA's Earth Observatory

Tiny Sea Creatures Hold Secrets to Earth's Climate

Denise Lineberry, NASA's Langley Research Center, denise.a.lineberry@nasa.gov

EDITOR'S NOTE: This article is taken from *nasa.gov*. While it has been modified slightly to match the style used in *The Earth Observer*, the intent is to reprint it with its original form largely intact.

Each new season brings change. Seasonal change on land is something that we're familiar with and adjust to regularly. But what happens to billions of plankton in the ocean each season? How do they adjust to changing sunlight patterns and mixing of the water column? And what impact do these tiny critters have on us, so far away on land?

To answer those questions and others, NASA's North Atlantic Aerosols and Marine Ecosystems Study (NAAMES)¹ mission began its fourth and final deployment, making it the first research mission to conduct an integrated study of all four distinct phases of the world's largest phytoplankton bloom in the North Atlantic and how they impact the atmosphere.

"Most scientists studying the bloom head to sea during its climax in late spring and early summer. We did that, but we also went out during the other seasons to fully capture the minimum and transitions of the bloom," said **Rich Moore** [NASA's Langley Research Center (LaRC)—*NAAMES Deputy Project Scientist*]. "This thoroughness pays off as our ship-based scientists use these data to fully describe the entirety of the plankton bust/boom cycle," he said. "No one has done this before, and we're excited about the science findings that are beginning to trickle out now."

NAAMES research challenges traditional ideas about bloom dynamics and species succession. Findings from three deployments have already confirmed a distinct shift in the annual cycle of the phytoplankton bloom and researchers have noted a clear lack of

¹NAAMES is an interdisciplinary investigation resolving key processes controlling marine ecosystems and aerosols that are essential to our understanding of Earth system function and future change. NAAMES is one of five missions funded in the first NASA Earth Venture Suborbital (EVS-1) Announcement of Opportunity. To learn more, visit <https://naames.larc.nasa.gov/science.html>.

larger-sized plankton during the peak of the bloom. The implication of these findings will be presented in a series of journal publications over the coming year.

During previous NAAMES deployments, researchers completed 220 research hours aboard an instrumented C-130 aircraft along specific tracks and maneuvers over the North Atlantic, including fly overs of the Woods Hole Oceanographic Institution Institute's (WHOI) Research Vessel *Atlantis* (shown in photo below), which carries more than 50 researchers and crew members.

The ongoing ship deployment is currently collecting observations of ocean biological composition and stocks, aerosol measurements, and optical properties of the North Atlantic study area.

Satellites such as the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), a joint NASA and Centre National d'Études Spatiales (CNES) mission, also help to study the ocean and the atmosphere—from the depths of the phytoplankton bloom, to the clouds and atmospheric particles in the sky above.

This final NAAMES study researches the *ascending transition* of the bloom which occurs after the phytoplankton minimum in February. In the March-April phase, the plankton are growing steadily, with their abundance in the water continuing to increase or accumulate toward the maximum of the bloom between May and July.



A view of the Woods Hole Oceanographic Institution (WHOI) Research Vessel *Atlantis*, the ship used during the North Atlantic Aerosols and Marine Ecosystems Study (NAAMES). **Photo credit:** Nicole Estaphan

This bloom phase provides a unique opportunity for researchers aboard Atlantis to do experiments that study growth and decay of the phytoplankton population.

“For scientists watching the rates of growth, this is the exciting time, because the accumulation rate is expected to be going through the roof and stay high for the next few months,” Moore said. Rates of phytoplankton accumulation are critical for understanding the ocean conditions that lead to phytoplankton growth and its timing, a key to unlocking the environmental drivers and controls of biological dynamics.

Because scientists are also interested in the link between the ocean, atmospheric particles, and clouds, they’ve conducted meteorological balloon launches from the ship on a regular basis to capture information relevant to cloud formation processes.

By combining global data from NASA satellites with the ship, aircraft, and autonomous assets such as floats, along with laboratory research and balloon data, scientists are able to not only understand the current state of the atmosphere, but also how it is evolving over time.

“At this point in the study, we’re using the logistical lessons learned from the first three deployments to execute what is needed to fill in the last piece of the science puzzle about what drives the accumulation phase for phytoplankton growth,” Moore said. “Then the real fun starts,” he said, referring to the ongoing analyses of the data and publication of findings in scientific journals. ■

Undefined Acronyms Used in Editorial and Table of Contents

CALIPSO	Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations
EDT	Eastern Daylight Time
GPS	Global Positioning System
GRACE–FO	Gravity Recovery and Climate Experiment Follow-On
GSFC	NASA’s Goddard Space Flight Center
ICESat	Ice, Cloud and land Elevation Satellite
JPL	NASA/Jet Propulsion Laboratory
METI	Ministry of Economy, Trade, and Industry
PDT	Pacific Daylight Time
USDA	U.S. Department of Agriculture



NASA Earth Science in the News

Samson Reiny, NASA's Goddard Space Flight Center, Earth Science News Team,
samson.k.reiny@nasa.gov

April's CO₂ Levels Had the Highest Average in Recorded History, May 4, *slashgear.com*. Carbon dioxide (CO₂) was measured at record levels in April 2018. According to Scripps Institution of Oceanography, the Mauna Loa Observatory in Hawaii measured the atmosphere's average CO₂ concentration level at 410.31 ppm. That's the highest monthly average in recorded history. According to Scripps, pre-Industrial Revolution levels had never managed to tip past the 300 ppm threshold. In fact, the monthly average in April was one of the highest figures reached in the last 800,000 years. NASA shows the most recent CO₂ measurement at 408 ppm taken in March 2018. NASA provides a download containing the data for anyone interested (<https://climate.nasa.gov/vital-signs/carbon-dioxide>).

Old Arctic Sea Ice Is Virtually Gone—and That's Bad, May 4, *earth.com*. The winter of discontent in the Arctic has morphed into a spring of discontent. Shocking new data show that the region has lost almost all its old sea ice. Its disappearance, driven by warming waters and rising air temperatures, means the region is losing a bulwark against even more dramatic sea ice loss. On May 3, 2018, the National Snow and Ice Data Center (NSIDC) released its monthly sea ice analysis. It shows that April saw its second-lowest sea ice extent on record, driven by a massive meltdown in the Bering Sea (ice started melting there during Arctic winter). "It's the end of April and basically the Bering Sea is ice-free, when normally there would be more than 500,000 km² (greater than 193,000 mi²) of ice," **Walt Meier** [NSIDC—*Scientist*] told NASA's *Earth Observatory*. "It is at a record low extent for most of 2018 and has continuously been a record low since February 12." But there's another harrowing statistic in NSIDC's report. Old Arctic ice is at its lowest level ever recorded through the first nine weeks of 2018. Ice older than one year covered 61% of the region in 1984 during that initial nine-week period. In 2018 it covered just 34%. Just 2% of the Arctic's sea ice is 5 years old or older—compared to 30% in 1984.

Dwindling Desert Dust Spells Danger for the Amazon, May 7, *cosmosmagazine.com*. Global warming may cut the amount of dust blown into the atmosphere from the Sahara Desert by up to 100 million tons a year, starving the Amazon rainforest of nutrients and turning up the heat in the North Atlantic. Rising temperatures will mean less wind and hence less dust, according to a paper (<https://arxiv.org/pdf/1804.07188.pdf>) by **Tianle Yuan** [NASA's Goddard Space Flight

Center—*Earth Scientist*] and colleagues. Previous attempts to predict future dust levels have had limited success, but the new publication argues that previous studies have ignored the key factor: the temperature difference between the North and South Atlantic. Airborne dust is a surprisingly large player in the planet's climate system: it both absorbs and scatters radiation from the sun, serves to seed clouds by providing nuclei for water droplets to grow around, and—when it finally falls back to the surface—can provide key minerals such as iron and phosphorus for plants and marine life. The amount of dust in the atmosphere in turn depends on climatic conditions such as temperature, rainfall, and wind speeds. As the world warms, climate scientists expect that the northern part of the Atlantic Ocean will get hotter faster than the southern part. Southern Hemisphere winds will rush northward to balance out the temperature contrast, meaning that the area where air circulation from the two hemispheres meets—a blustery band of latitude known as the *inter-tropical convergence zone* (ITCZ)—will drift northward. This all adds up to weaker winds over the Sahara, resulting in less dust in the air. Another effect of the airborne dust is to provide shade that cools the North Atlantic. As the dust dwindles, clearer air will mean warmer seas—which in turn means less dust. Yuan's team calculated that the amount of dust could drop by as much as 60% by the end of the twenty-first century. The decline in dust levels may become a self-reinforcing cycle.

NASA's GRACE-FO Mission with GFZ to Offer Insight into Earth's Water Cycle, April 30, *inquisitr.com*. After the resounding success of the 15-year-long Gravity Recovery and Climate Experiment (GRACE) mission, NASA is getting ready for GRACE – the sequel. The U.S. space agency is once again teaming up with the German Research Centre for Geosciences (GFZ) to kick off the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission. GRACE-FO will continue to keep an eye on Earth's water cycle by monitoring the monthly changes of mass distribution that occur in our planet's atmosphere, ocean, land, and ice sheets. At the same time, the mission will be studying what goes on under the Earth's crust all the way up from space. The satellites will be able to detect the movement of massive amounts of water, ice, and solid crust on Earth by determining how this movement affects the shape of the planet's gravity field. Essentially, the GRACE-FO satellites will use the weight of water to measure its movement and provide a birds-eye view on the goings-on in Earth's water cycle

by tracking changes in water mass. This applies not only to the planet's oceans but also to the polar ice sheets and the deep water that flows under the crust.¹

Global Temperatures Have Dropped Since 2016.

Here's Why That's Normal, April 26, *washingtonpost.com*. It was only two years ago that a new record-warm global temperature was set, but things have already cooled off significantly. Temperature anomalies hit record peaks in 2016, but have been sliding since then. Global temperatures are still much warmer than normal, but according to NASA, the first quarter of 2018 (January–March) was the fourth warmest, behind 2015, 2016, 2017, and tied with 2010. This is normal, of course. The world has not seen the last of global warming. The long-term upward trend in temperatures is the result of man-made fossil fuel emissions, but natural processes that affect global temperature—like El Niño (very warm waters in the central Tropical Pacific)—still play a role. Sometimes they make things warmer and sometimes they make things cooler. The

¹ To learn more about GRACE-FO see the feature article on page 4 of this issue.

current cooling episode is mostly the result of a reversal of waters in the Tropical Pacific, which can modulate global temperature. Since the Pacific Ocean is our largest global body of water, what it does makes a big difference on global climate. A similar reversal followed the super El Niño in the late 1990s—1998 was the hottest year on record at the time in part because of the warm El Niño water pushing global temperatures higher. Earth went from having one of the strongest El Niño events on record to a few years of cooler waters, thanks to a La Niña period. Natural processes like El Niño and La Niña are why we end up with a lot of fluctuation, but overall the global temperature trend is up.

*Interested in getting your research out to the general public, educators, and the scientific community? Please contact **Samson Reiny** on NASA's Earth Science News Team at samson.k.reiny@nasa.gov and let him know of upcoming journal articles, new satellite images, or conference presentations that you think would be of interest to the readership of **The Earth Observer**. ■*

EOS Science Calendar | Global Change Calendar

June 4–6, 2018

ASTER Science Team Meeting,
Tokyo, Japan.

September 24–29, 2018

OST Science Team Meeting,
Ponta Delgada, Azores, Portugal.
[https://www.altimetry2018.org/
QuickEventWebsitePortal/25-years-of-progress-in-radar-
altimetry-symposium/esa](https://www.altimetry2018.org/QuickEventWebsitePortal/25-years-of-progress-in-radar-altimetry-symposium/esa)

April 1–4, 2019

ABOVE Science Team Meeting,
La Jolla, CA.

June 3–8, 2018

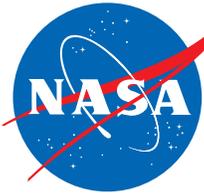
Asia Oceania Geosciences Society,
Honolulu, HI.
[http://www.asiaoceania.org/aogs2018/public.
asp?page=home.htm](http://www.asiaoceania.org/aogs2018/public.asp?page=home.htm)

July 14–22, 2018

COSPAR 2018 Assembly,
Pasadena, CA.
<http://cospar2018.org>

September 24–29, 2018

25 Years of Progress in Radar Altimetry Symposium
Ponta Delgada, Azores, Portugal.
[https://www.altimetry2018.org/
QuickEventWebsitePortal/25-years-of-progress-in-radar-
altimetry-symposium/esa](https://www.altimetry2018.org/QuickEventWebsitePortal/25-years-of-progress-in-radar-altimetry-symposium/esa)



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The Earth Observer

The Earth Observer is published by the Science Communication Support Office, Code 610, NASA's Goddard Space Flight Center, Greenbelt, Maryland 20771, telephone (301) 614-5561, FAX (301) 614-6530, and is available in color at *eospso.nasa.gov/earth-observer-archive*.

Articles, contributions to the meeting calendar, and suggestions are welcomed. Contributions to the calendars should contain location, person to contact, telephone number, and e-mail address. Newsletter content is due on the weekday closest to the 1st of the month preceding the publication—e.g., December 1 for the January–February issue; February 1 for March–April, and so on.

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The Earth Observer Staff

Executive Editor:	Alan B. Ward (alan.b.ward@nasa.gov)
Associate Editor:	Heather H. Hanson (heather.h.hanson@nasa.gov)
Assistant/Technical Editor:	Mitchell K. Hobish (mkh@sciential.com)
Technical Editor:	Ernest Hilsenrath (hilsenrath@umbc.edu)
Design, Production:	Deborah McLean (deborah.f.mclean@nasa.gov)



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